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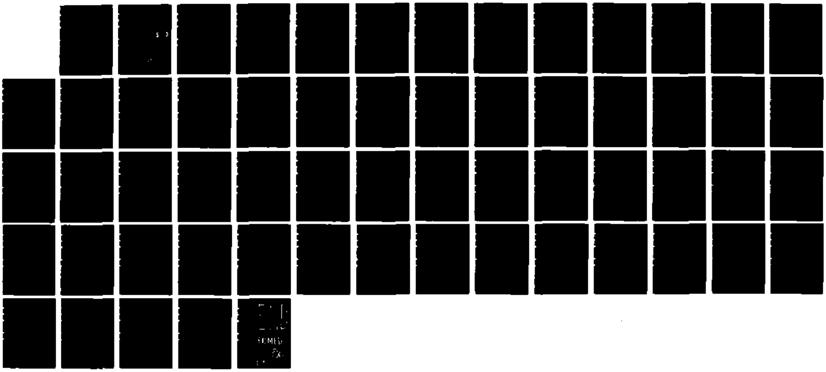

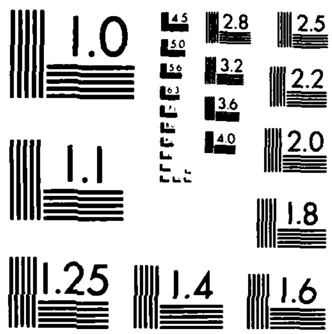

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Test Results for Developing Revised LORAN-C Protection Criteria

AD-A164 139

F.W. Mooney

Transportation Systems Center
Cambridge MA 02142

November 1985
Final Report

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16. Abstract

This report presents the results obtained from a series of tests and related analyses studying the effect of harmful RF interference on LORAN-C receivers. The effects of interference in the 70 to 130 kHz band on typical LORAN-C receivers were assessed. Recommendations were developed for signal-to-interference ratios and protection boundaries that would permit proper receiver operation during conditions of interference.

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PREFACE

This report presents the results obtained from a series of tests and related analyses detailing the effect on LORAN-C receivers of unwanted interference similar to that which can be created by radio communications and radionavigation facilities operating within the 70 kHz to 130 kHz frequency band.

While LORAN-C transmitters are required to transmit a minimum of 99 percent of their radiated power within the band 90 to 110 kHz, LORAN-C receiver bandwidths must be greater than this amount in order for the receiver to effectively operate. Thus, the receivers should be regarded as vulnerable throughout the broader frequency band 70 to 130 kHz.

The results of this activity are to be utilized by the U.S. Coast Guard in preparing a set of recommendations to be presented to the International Radio Consultative Committee of the International Telecommunications Union in support of the U.S. Government's request for protection of the LORAN-C radionavigation system.

The principal data gathering effort was accomplished by the USCG Electronics Engineering Center (EECEN) in accordance with a Test Plan prepared by the U.S. DOT/Transportation Systems Center.

Personnel from the Transportation Systems Center, Cambridge Engineering, Polhemus Associates, Inc., and the USCG EECEN were participants in the project. Subsequent analyses and preparation of the report were the responsibilities of the Transportation Systems Center and the cited Contractors. Special thanks is expressed to M.C. Poppe of Cambridge Engineering, W.L. Polhemus of Polhemus Associates, Inc., and Lt. David Beard of the USCG EECEN for their outstanding contributions to this project.

The project was sponsored by DOT/U.S. Coast Guard, Radionavigation Division, G-NRN.

3

GLOSSARY OF FREQUENT ABBREVIATIONS

CA	Combined Accuracy $CA = (MTDE^2 + TD^2)^{1/2}$
CWI	Continuous Wave Interference
EECEN	USCG Electronics Engineering Center
LRTC II	LORAN Receiver Test Complex II
rms	root mean square
rss	root sum square
SIR	Signal-to-Interference Ratio
TD	Time Difference
MTDE	Mean Time Difference Error
WB	Wideband
NB	Narrowband
S.D.	Standard Deviation
FSK	Frequency Shift Keyed
RATT	Radio Teletype
SNR	Signal-to-Noise-Ratio
GRI	Group Repetition Interval

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

This report describes the results obtained from a series of tests conducted by the U.S. Coast Guard and the Department of Transportation (DOT) Transportation Systems Center (TSC) contractor personnel at the USCG Electronics Engineering Center in Wildwood, N.J., in accordance with instructions contained in DOT/TSC, "Test Plan to Develop Revised LORAN-C Protection Criteria".

The purpose of the tests was to subject five typical LORAN-C receivers to harmful radio communications interference. The conclusions derived from this effort have been utilized by DOT/TSC and the USCG to support the U.S. Government's request for protection of the LORAN-C radio frequency (RF) band 70 to 130 kHz.

Between frequencies 70 kHz and 130 kHz, a number of different radiocommunications and radionavigation services worldwide have been approved for transmission on specific frequencies by the International Telecommunications Union (ITU). When these signals overlap with sufficient intensity, they produce harmful interference affecting these services.

The International Radio Consultative Committee (CCIR) of the ITU has responsibility for formulating recommendations on an international level regarding use of the radio communications and radionavigation frequency spectrum. Because of the adverse consequences of some types of RF interference on radionavigation systems, particularly the Decca Navigator system and the LORAN-C radionavigation service, the CCIR solicited technical advice from the advocates of the Decca system and from the U.S. Coast Guard regarding the LORAN- C system.

It is necessary to recognize that safety considerations relevant to performance of the LORAN-C radionavigation service (and also the Decca system) make it essential that they be able to operate free from harmful interference.

While LORAN-C transmitters are required to transmit a minimum of 99 percent of their radiated power within the band 90 kHz to 110 kHz, LORAN-C receivers require bandwidths greater than 20 kHz in order for the receiver to be effective.

The problem of providing suitable protection to the LORAN-C and Decca Navigator systems has been under study by the International Telecommunications Union (ITU). During its 15th Plenary Assembly (Geneva, 1982) the CCIR concluded in Report 915[1] that for planning purposes, when acceptance of a new transmitting signal is considered within the 70 kHz - 130 kHz band, the Decca Navigator system should be protected by assuring a nominal relative signal-to-interference buffer or ratio between the system and the new transmission of +15 dB. An additional allowance of +6 dB was allocated to protect the Decca system from skywave interference at night. The criteria were developed from data obtained in laboratory testing.

It was desired to prepare a similar, quantitatively-based criteria, for protection of the LORAN-C radionavigation system; however, the appropriate test data were not available when the U.S. Government submission was prepared.

The guidelines for preparation of the U.S. response are in CCIR 'Question' 33/8 which reads as follows:

CCIR QUESTION 33/8

1 - What system parameters must be defined to assure compatability and to avoid harmful interference between the radionavigation services and other services authorized in the bands between 70 kHz and 130 kHz;

2 - What system factors may cause interference between different types of radionavigation systems operating in these bands;

3 - What operational characteristics should be recommended to avoid mutual interference between stations providing the same type of radionavigation service?

A U.S. Government response to these concerns, prepared by the U.S. Coast Guard, was formulated as an Amendment to the CCIR's Report 915. It required supporting data which could be used to correlate types and relative strengths of RF transmissions appearing in the 70 kHz to 130 kHz band with the performance of typical state-of-the-art LORAN-C receivers.

When available, the data were to be synthesized as a protection criteria and subsequently used to assist in evaluation of requests for new frequency assignments within this band.

The U.S. Coast Guard's Electronics Engineering Center (EECEN) was given the task to conduct a series of tests which would provide the basis for a quantitative response to the 'Question' 33/8 previously described. EECEN was assisted in this effort by the DOT/TSC, at Cambridge, MA, which prepared the Test Plan and completed analyses of data. The data were subsequently used to formulate a criteria for assuring compatibility with other authorized radionavigation systems and avoidance of harmful interference between and among the services authorized to operate within the 70 kHz - 130 kHz band.

This report describes the development of the test criteria, the tests undertaken by EECEN, the nature of the interferences imposed on the five selected LORAN-C receivers, results and conclusions obtained from analysis of the data.

The report includes suggested criteria for protection of the LORAN-C radionavigation system, and offers a procedure for assessing the effect of multiple interfering signals on LORAN-C receiver performance.

2. BACKGROUND

2.1 GENERAL

LORAN-C receiver performance is susceptible to two general types of radio frequency interference:

- Those of an amplitude form which modulate the LORAN-C signal envelope or mask the desired zero crossing (tracking) point due to the signal strength of the interfering RF transmission;
- Those which are synchronous or near-synchronous, in the time domain, with the spectral lines associated with the LORAN-C pulse rate in use.

Because the ITU authorizes several radionavigation, fixed, and maritime mobile services in the bands between 70 kHz and 130 kHz; and because these radionavigation systems may be either pulse or continuous wave (CW); and because typical LORAN-C receiver systems must be capable of acquiring and subsequently tracking relatively weak transmissions, it was necessary that the interference tests be capable of measuring receiver performance under varying but known and controlled conditions of relative signal-to-interference field strength and interfering frequency.

2.2 TYPES OF INTERFERENCE

The recognized reference for defining LORAN-C signal characteristics, required receiver performance, types of interference and their potential effects is the RTCM SC-70 publication, Minimum Performance Standards (MPS) for Marine LORAN-C Receiving Equipment[2] as described in RTCM Paper 12-78/DO-100.* There are three categories of interference and three types of emissions of concern to LORAN-C receivers discussed therein and reviewed below.

2.2.1 Synchronous Interference

Synchronous transmissions are those which produce spectral lines which are in phase with those of the LORAN-C pulse pattern. They cause a constant error in the measured LORAN-C time difference (TD) and thus in radionavigation accuracy.

2.2.2 Near-Synchronous Interference

Near-synchronous transmissions, while not in phase with the LORAN-C pulse pattern, are those whose spectral lines fall within the bandwidth of the servo tracking loop of the receiver.

Note: Synchronous/near-synchronous interfering signals cause increases in the mean time difference error (MTDE) of the receiver through their effect on the signal phase tracking circuits.

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* A separate MPS is being prepared for avionics receivers by the Radio Technical Commision for Aeronautics. When completed, separate tests may be appropriate for avionics LORAN-C receivers.

2.2.3 Non-Synchronous Interference

Non-synchronous transmissions of sufficient amplitude to cause interference with the received LORAN-C signal contribute to an increase in the variations of time difference error about the mean value and are described in terms of standard deviation (S.D.). This kind of interference is significant when its relative signal strength enables it to mask the envelope start point, the desired zero-crossing (tracking) point, or the shape of the LORAN-C pulse.

2.2.4 Types of Emissions

There are three principle types of emissions of concern to this study, Continuous Wave (CW), Narrowband Frequency Shift Keyed (FSK), and Wideband FSK.

2.2.4.1 Continuous Wave Interference (CWI). Emissions of this type are narrowband and usually can be rejected through implementation of notch filters. The number of such CWI sources can be of concern. When the frequency of the CW interference lies within the 90 kHz to 110 kHz frequency band, special consideration must be given to its possible effect since application of notch filters within this band may degrade the receiver's ability to evaluate envelope shape and thus may prevent the receiver from locking on to (acquiring) the desired tracking point (cycle).

2.2.4.2 Narrow Band Frequency Shift Keyed (FSK) Communications. Emissions of this type consist of bands of energy centered about a specified carrier frequency. The frequency shift usually occurs within a range of 150 to 400 Hz. One of two frequencies is being emitted at any instant.

2.2.4.3 Wideband Frequency Shift Keyed (FSK) or Multichannel Radio Teletype (RATT) Communications. Emissions of this third type are similar to narrowband FSK except that the transmissions are completed on several channels which are changed at arbitrary intervals and spaced over several kHz.

2.2.5 Summary

Data were required for each of the combinations of interference summarized in Table 2-1 below.

TABLE 2-1. DATA REQUIREMENTS BY TYPE OF INTERFERENCE

		CATEGORY OF INTERFERENCE		
MODE	TYPE OF EMISSION	SYNC	NEAR SYNC	NON SYNC
Acquisition	CW Interference	--	X	X
	FSK Narrowband	--	X	X
	FSK Wideband	--	X	X

3. TECHNICAL APPROACH

3.1 GENERAL

Facilities at the USCG's Electronics Engineering Center (EECEN) were utilized for the tests since they offered the capability to simulate unwanted RF interference, the specified LORAN-C signals and the environmental conditions of interest.

3.2 FACILITIES AND EQUIPMENT

3.2.1 Navigation System Simulator

The simulator complex, which employs the LORAN-C Receiver Test Complex (LRTC II)[3] as its primary instrument, also includes:

- Rockland Remotely Programmable Frequency Synthesizer, Model 110 narrowband CW generator
- Hewlett-Packard Automatic Synthesizer, Model 3303B wideband, multi-channel, FSK emulator
- Wavetek HF Sweep Generator - narrowband FSK emulator.

The LRTC II is a second generation (Coast Guard designed) receiver test facility located in a dedicated facility within the EECEN. The simulator provides repeatable (and fully documented) signal conditions for measuring the performance of LORAN-C (and LORAN-D) receivers. It features high accuracy and resolution and provides means for complete control of the LORAN pulse. In addition, it offers a full complement of interference sources, including a simulated atmospheric noise source. The system is buss oriented with all parameters controllable from a central location.

3.2.2 LRTC II Setup

The LRTC II was set up as follows (see Figure 3-1):

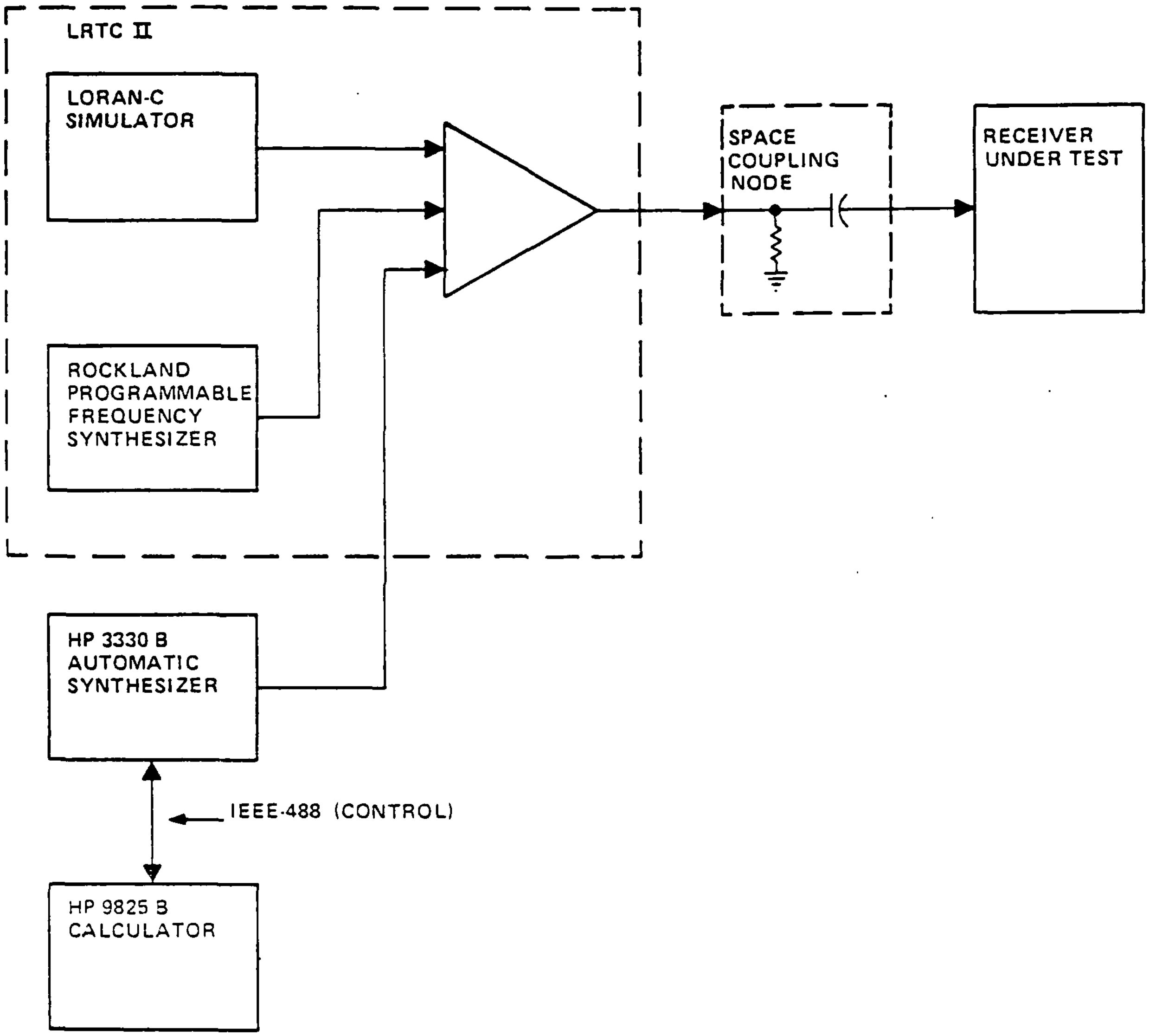

FIGURE 3-1. LRTC II EQUIPMENT SETUP

Control Parameter	Setting
• Group Repetition Interval (GRI)	9960
• Stations	M,W,X,Y,Z (M is the master station) (W,X,Y,Z are secondary stations) (W is used to evaluate performance)
• Signal Strength	M-70, W-40 (Referenced to dB/1 microvolt/meter)
• Atmospheric Noise	50 dB/1 microvolt/meter (1/3 SNR for 9960-W)
• Gaussian Noise	OFF (except as noted in Section 4)
• Skywave Interference	OFF
• Envelope-to-cycle differences	M 1.0μs; W,X,Y,Z -1.5μs
• Cross-rate Interference	OFF
• RF Interference	As necessary to determine receiver error.

(1) Relative field strength or Signal-to-Interference Ratio (SIR) - varied within the range +30 dB to -50 dB.

(2) Kinds of Interference - LRTC II adjusted to simulate near-synchronous and non-synchronous interference in accordance with the Test Plan.

(3) Types of Emissions - LRTC II inputs varied to produce CWI, narrowband and wideband FSK in accordance with the Test Plan.

- Specific Interferences:
  - CWI, near-synchronous to be set within 0.006 Hz of the LORAN spectral line; e.g., within the servo bandwidth of the receivers.
  - Frequency Shift Keying, (FI) (narrowband); set up a single channel with 170 Hz shift, one tone to be near-synchronous.
  - Multiple-Channel Frequency Shift Keying, (F9); set up utilizing 11 channels, 3 kHz total bandwidth.

3.2.3 State-of-the-art LORAN-C Receivers

Five LORAN-C receivers were provided to the USCG by TSC: three marine and two airborne radionavigation (RNAV) systems. The receivers were of hard limited design and were selected because they were typical of those available in the marketplace. The three marine receivers represented the high, medium, and low ends of the market while the two airborne receivers represented the medium and low end of their respective market. Thus, their response to the RFI tests were representative of the manner in which most state-of-the-art receivers would behave under similar circumstances.

3.2.4 Setup of LORAN-C Receivers

The notch filters were to have been disabled in each receiver. However, as will be discussed in Section 4, the procedures recommended by the manufacturers were not always successful.

The receivers were operated using Group Repetition Interval (GRI) 9960 which is the assigned GRI for the Northeast United States.

3.3 PARAMETERS OF TESTS

3.3.1 Assumptions

- Receiver bias error would be constant (or could be normalized) for the tests;
- Receiver tracking bandwidth could be established through step response tests as described in the USCG's "Five Day Test Plan" -- Project WO944- A4
- Insertion of interference into the simulated LORAN-C signal with simulated atmospheric noise would permit establishment of 0.3 microsecond error limits for a band of frequencies. It was expected that the receivers would exhibit less susceptibility as the interfering frequency, f_i, was displaced further from 100 kHz;
- The LORAN-C signal strength as measured at EECEN is representative of typical service areas. This was used to establish signal levels for all stations.

3.3.2 Types of Tests

3.3.2.1 Frequency-Related Forms of Interference. CCIR Report 915 as amended by Revision 1 states that a 1.0 Hz protected bandwidth around LORAN-C spectral lines is desired. This is predicated on the observation that marine receivers typically exhibit a response of 0.01 Hz, that airborne receivers exhibit a response of 0.1 Hz, and that a safety factor of 10:1 is sufficient to permit normal receiver operation. To verify this criterion, the receiver tracking bandwidth was determined for each receiver.

3.3.2.2 Amplitude-Related Interference. The rms signal level of the LORAN-C pulse, as defined at the standard sampling point, was compared with the rms level of the interference to obtain a measure of signal-to-interference ratio (SIR).

3.3.3 Test Criteria

The principal criteria of testing were:

1) verification of the characteristics of receiver tracking bandwidths of less than 0.01 Hz for marine receivers and 0.1 Hz for airborne receivers;

2) determination of the combinations of emitter frequency and relative signal strength at which the LORAN-C test receiver accuracy degraded to 0.3 microsecond.

The 0.3 microsecond time difference error is that which is allowed in the RTCM Minimum Performance Standards,[2] the U.S. standard for measuring performance of LORAN-C receivers.

3.3.4 Test Procedures

3.3.4.1 Receiver Biases. All identified receiver biases, determined before introduction of any interference, were tagged and eliminated from the data before assessing TD error performance. The Test Plan required that the receiver undergoing test be held at the correct tracking point, i.e., nominal 0.0 microsecond TD error.

3.3.4.2 Tracking Bandwidth. The tracking bandwidth of each receiver was established in accordance with the procedures outlined in the Coast Guard's standard "Five Day Test Plan". The objective of this test was to confirm that the 'typical' receiver servo bandwidth was less than 0.01 Hz for marine receivers and 0.1 Hz for airborne units.

3.3.4.3 Independence of Measurements. All observations and measurements taken during the interference tests were controlled and or timed to be statistically independent (95 percent confidence).

3.3.4.4 Validation Tests. The TSC team returned to EECEN following assessment of the data gathered during the principal signal-to-interference ratio tests for the purpose of conducting a series of test validation measurements. These tests included a limited sample of receiver acquisition tests as well as a repetition of selected sets of S/R tracking measurements. Gaussian and atmospheric noise sources were employed. Correlation of required signal to noise levels with selected noise sources was made.

3.3.4.5 Retention of Data. All test instrumentation set-ups and tests were documented so that they could be repeated at a later date as required. All raw data acquired during the test program and related project notebooks will be retained for a period of 5 years. This will insure that supportive data is available throughout the next CCIR 4-year cycle.

3.4 SIMULATING INTERFERENCE AND SELECTING FREQUENCIES[3]

3.4.1 Near-Synchronous Interference

In this test program the effect of near-synchronous interference was evaluated by setting the carrier frequency (f_c) of the interferer so that it satisfied the relationship:

$$\left| f_c - \frac{N}{2\,GRI} \right| < f_b$$

where f_b is the tracking bandwidth of the receiver, N is any integer and GRI is the LORAN-C Group Repetition Interval (GRI) under consideration.

Near-synchronous interference frequencies throughout the 70 to 130 kHz band were mixed with LORAN-C signals. Spectral spacing of 0.006 Hz was maintained at each test frequency.

3.4.2 Non-Synchronous Interference

The effect of non-synchronous interference was evaluated by setting the carrier frequency of the unmodulated interference halfway between two spectral lines of the LORAN-C signal.

3.4.3 Emission Bandwidths

The combinations of frequencies, types of emissions and modulation indices in use by various agencies is enormous. Tests for all combinations would have been impractical. The following test conditions were selected as representative of emission types.

- CW Emissions - bandwidth less than 6 Hz, within 0.001 Hz of f_i, where f_i is the interfering frequency.
- Narrowband FSK ± 85 Hz modulation, centered about f_i, Baud Rate 110
- Wideband FSK - 10 channels, 300 Hz spacing, centered about f_i, with total emission bandwidth of 3 kHz, Baud Rate 300.

3.5 FREQUENCY ASSIGNMENT

3.5.1 Nominal Assignment

Frequency assignments for the signal to interference tests were spread throughout the 70 to 130 kHz band. Ten frequencies were evaluated for CW and wideband FSK interference. Evaluation of only five frequencies for narrowband FSK were made since performance patterns became obvious after conducting the CW and wideband FSK tests.

The nominal frequencies of the interferences selected were:

a.	72 kHz	f.	101 kHz
b.	78 kHz	g.	107 kHz
c.	84 kHz	h.	113 kHz
d.	90 kHz	i.	119 kHz
e.	96 kHz	j.	125 kHz

3.5.2 Specific Frequency Assignment

The specific frequencies selected are shown in Table 3-1 and were derived as follows:

a. For near-synchronous types of interference, the specific frequency was selected from: $f_i = f_s + 0.006$ Hz, where f_s was the closest spectral line to the nominal frequency.

b. For non-synchronous types of interference, the specific frequency was identified from: $f_i = f_s + 1/2$ spectral spacing.

c. Frequency Calculations: Since Loran is a pulse modulated transmission, it has discrete spectral lines. The spectral line spacing is inversely proportional to the pulse rate or Phase Code Interval (PCI):

$$f_{sp} = \frac{1}{PCI} \text{ or } \frac{1}{2\,GRI} \quad (1)$$

where: f_{sp} = spectral line spacing

PCI = Phase Code Interval

GRI = Group Repetition Interval

for: GRI = 99600 microseconds

$$f_{sp} = \frac{1}{2\,(99600\ \mu s)} \quad (2)$$

$$f_{sp} = 5.0201\ Hz \quad (3)$$

TABLE 3-1. SPECIFIC FREQUENCIES

NOMINAL FREQUENCY	INTERFERENCE PERIODS IN 1300μS (Note 1)	APPROXIMATE FREQUENCY (Note 2)	NEAREST SPECTRAL LINE NO. (Note 3)	SPECTRAL LINE FREQUENCY
72 kHz	936	72038 Hz	5570	72038.153 Hz
78 kHz	1014	78038 Hz	4374	78042.169 Hz
84 kHz	1092	84038 Hz	3180	84036.145 Hz
90 kHz	1170	90038 Hz	1984	90040.161 Hz
96 kHz	1248	96038 Hz	790	96034.137 Hz
101 kHz	1313	101038 Hz	206	101034.137 Hz
107 kHz	1391	107038 Hz	1402	107038.153 Hz
113 kHz	1496	113038 Hz	2598	113042.169 Hz
119 kHz	1547	119038 Hz	3792	119036.142 Hz
125 kHz	1625	125038 Hz	4988	125040.161 Hz

Notes: (1) Solving n in equation 6 using the nominal frequency and truncating to an integer

(2) Solving for f_i in equation 6 using n from column 2.

(3) Even spectral lines were used to avoid phase code uncertainty between groups. Number of spectral lines from the 100 kHz carrier frequency solving for N in equation 4.

The spectral lines are centered around 100 kHz.

To find a spectral line,

$$f_{sl} = f_c = \frac{N}{2\,GRI} \tag{4}$$

where: f_{sl} = spectral line frequency

N = an integer

f_c = 100 kHz carrier frequency

Next, the effect of the interference on master and secondary stations was considered. For a synchronous interference, if there were integer number of periods of interference between master and secondary, both stations would be "in-phase" and the TD error would be minimal because both stations would wander together

This effect was avoided by the choice of out-of-phase frequency selection, partly because of an amplitude difference between master and secondary, and partly because selection of interference frequency was restricted to an out-of-phase criterion.

That is:

$$\frac{n+1/2}{f_i} = TD \tag{5}$$

where: f_i = interference frequency

n = an integer

TD = time difference

or:

$$TD(f_i) = n + 1/2 \tag{6}$$

d. Modulation Calculations - A Frequency Shift Keyed (FSK) or F1 signal was also used in the tests. A binary FSK waveform with a continuous phase and constant envelope was used. The general expression for the waveform is:

$$Z(t) = A\cos(2\pi f_c t + 2\pi f_d(D(t)) + \theta) \tag{7}$$

where: D(t) = a random binary waveform with levels +1 when b_k = 1 and -1 when b_k = 0

f_c = carrier frequency

f_d = frequency deviation

b_k = bit stream, 0's or 1's

The instantaneous frequency, f_j, is:

$$f_j = f_c + f_d(D(t)), \text{ or} \tag{8}$$

$$= f_c + f_d \text{ for } D(t) = 1, \text{ or } bk = 1; \text{ or} \tag{9}$$

$$= f_c - f_d \text{ for } D(t) = -1, \text{ or } bk = 0 \tag{10}$$

For the tests,

f_d = 85 Hz

b_k = alternating 1's and 0's (squarewave), simulating a 100 baud data rate, 10 ms per bit.

For a large frequency shift compared to the data rate, major peaks in the power spectral density curve occur at the frequencies, $f_c + f_d$ and $f_c - f_d$. Impulses corresponding to the discrete frequency sinusoid components are not present because:

$$2fd \neq mrb \tag{11}$$

Where: m = any integer

r_b = bit rate

The exact frequencies used for testing are listed in Table 3-2 below. The frequencies were selected so that $f_c + f_d$ was 0.006 Hz from a LORAN-C spectral line.

e. Multi-Channel Simulation - A multiple channel signal was simulated by using a frequency synthesizer:

$$Z(t) = A \cos(2 \pi f_c t + 2 \pi f_a(a(t)) + \theta) \tag{12}$$

where: a(t) = n from 0 to 10

f_a = frequency increment

The instantaneous frequency, fj, is:

$$f_j = f_c + n f_a \tag{13}$$

For these tests, a 3 kHz bandwidth was used. Each frequency step, f_a, was 300 Hz. Eleven discrete frequencies were transmitted, one at a time, with phase continuity preserved. Each frequency was transmitted for 3 ms.

f. Interference Amplitudes - The signal-to-interference ratio, as used in these tests, was the ratio of the LORAN-C signal rms voltage at the standard 25 µs sampling point (SSP)*, and the interference rms voltage. A wide-band, true rms voltmeter was used to measure the interference levels.

TABLE 3-2. FREQUENCY ASSIGNMENTS FOR NARROWBAND FSK

Nominal Frequency (Hz)	Approximate Frequency (Hz)	Fc - Fd (Hz)	Fc + Fd (Hz)
78000	78038	77872.175	78042.175
90000	90040	89870.167	90040.167
101000	101034	100864.143	101034.143
113000	113042	112872.175	113042.175
125000	125040	124870.167	125040.167

* As defined in the RTCM Minimum Performance Standards for Marine LORAN-C Receiving Equipment.[2]

4. OBSERVATIONS

4.1 GENERAL

On-site review of the EECEN data and data-taking procedures, undertaken as directed in the Test Plan, revealed several unexpected observations:

1) Remarkably robust performance of marine receiver M_2 in the presence of near-synchronous continuous wave interference (CWI).

2) A high degree of sensitivity to CWI exhibited by marine receiver M_1, in light of the more typical performance measured when it was subjected to other types of interference.

3) A relative decrease in the sensitivity exhibited by several receivers to interference at 113 kHz.

In all cases a detailed review of the EECEN data, and a verification of the data through spot measurements, has shown the EECEN data-taking process to be sound.

4.2 RECEIVER TRACKING BANDWIDTHS

The tracking bandwidths of the test receivers were estimated from measurements of the receiver servo loop constants. The response time of each receiver to a step change in phase is shown in Table 4-1. Using the approximation $f = (1/2\ T)$, the bandwidths range from 0.07 Hz for the airborne receivers, to 0.01 Hz for the marine receivers.[4] These bandwidths are in agreement with the range of bandwidths assumed in the Test Plan, and validate the selection of frequencies 0.006 Hz from the synchronous lines as "near-synchronous".

TABLE 4-1. SERVO LOOP TIME CONSTANT

Receiver	Time Constant	Overshoot Average	Maximum Overshoot
A_1	2.4 seconds	14.0 seconds	0.3 seconds
A_2	2.2 seconds	8.0 seconds	0.2 seconds
M_1	4.0 seconds	0.2 seconds	0.1 seconds
M_2	12.0 seconds	0.0 seconds	0.0 seconds
M_3	7.0 seconds	5.6 seconds	0.1 seconds

4.3 INDIVIDUAL RECEIVER PERFORMANCE

4.3.1 Review of Data for Marine Receiver M_2

The data for receiver M_2, when compared with data from the other four receivers, indicated unusually high insensitivity to near-synchronous CWI for all test frequencies other than 101 kHz, as shown in Figure 4-1.

The tracking test graphs present Signal-to-Interference Ratio versus Frequency in the same relationship as is used in ITU-CCIR Report 915. Figure 4-1 presents three curves: the lower one identifying the locus of points at which the time difference (TD) combined accuracy (CA) error reached 0.15 microseconds; the second curve, identifies the locus of points at which TD CA error equals 0.2 microseconds; and the third curve establishes the points at which an error alarm of some kind occurred. Note that there is no 0.3 microsecond curve, the M_2 receiver annunciated an alarm before TD error had increased to 0.3 microseconds.

The unexpectedly 'robust performance' of receiver M_2 in the presence of near-synchronous CWI is illustrated by the steepness of the slopes of the three curves. The plot indicates that an emitter radiating at 100 kHz would create a 0.15 microsecond TD error at LORAN Signal-to-Interference Signal Ratio of + 10 dB and would prevent use of receiver M_2 at -5 dB.

However, note that at points ± 5 kHz from the LORAN central carrier frequency the data indicate that SIR may be reduced by 20 dB and at ± 10 kHz by ± 40 dB, or stated in terms of the interferer, the offending emitter can apparently produce a 40 dB stronger signal than would be tolerable at 100 kHz.

Figure 4-2 compares the response of all five receivers to near-synchronous CWI. In this illustration, only the 0.3 microsecond TD CA or Alarm Limit curves are presented. Receiver M_2 occupies the center of the plot. Each receiver exhibits quite a different response to the interference, but generally the other four receivers (M_1, M_3, A_1, A_2) are seen to require protection across a substantially wider bandwidth than receiver M_2, and receiver M_1 apparently requires an additional + 20 dB improvement in SIR.

Normally, the performance of receiver M_2 would be associated with either special receiver processing or an extremely narrow RF bandwidth. To verify the measured data, the non-synchronous CWI test was repeated at the 96 kHz (nominal) frequency. This repeat measurement verified the interference rejection capabilities originally measured by EECEN.

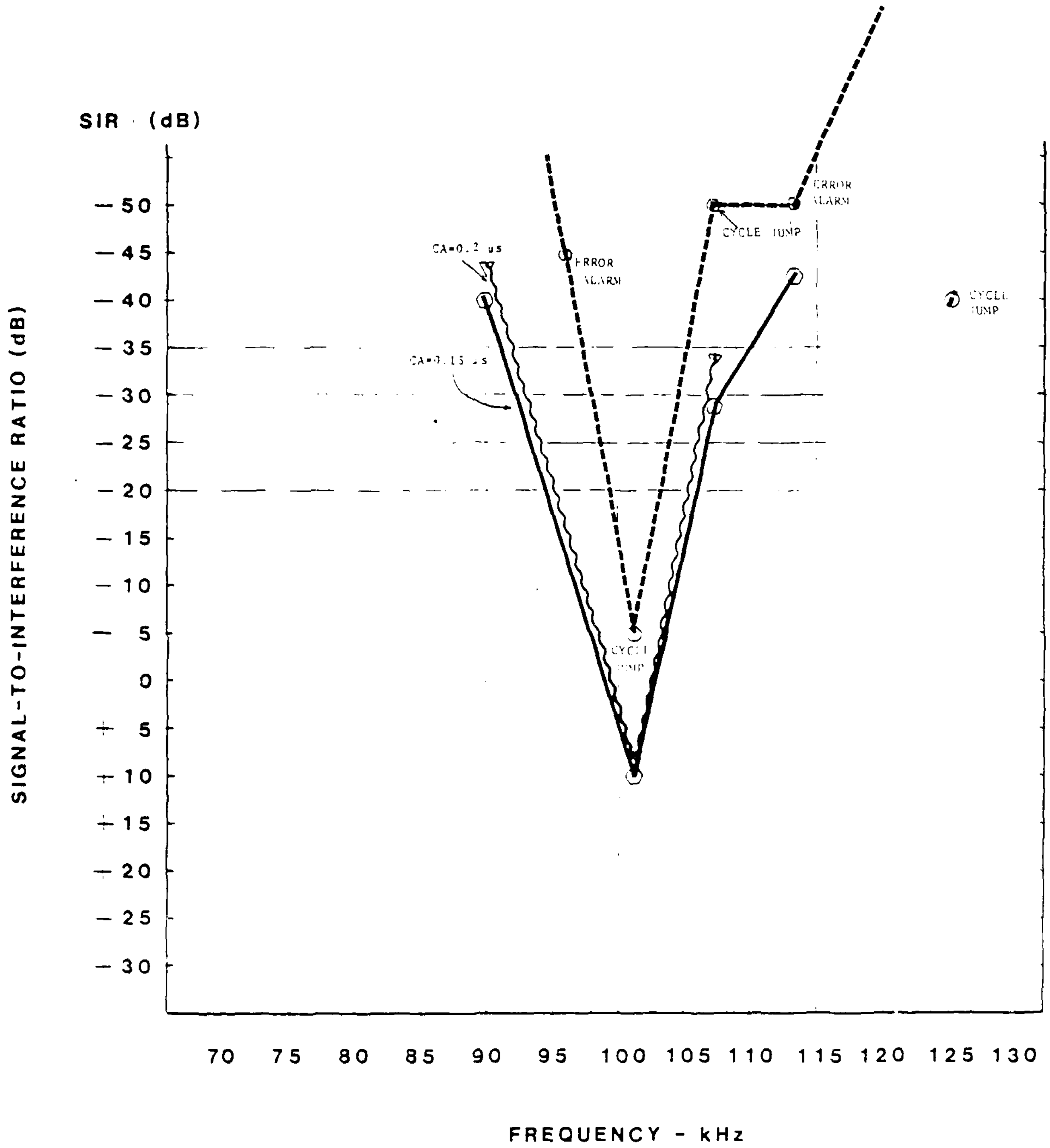

FIGURE 4-1. RECEIVER M_2 RESPONSE TO NEAR-SYNCHRONOUS CWI

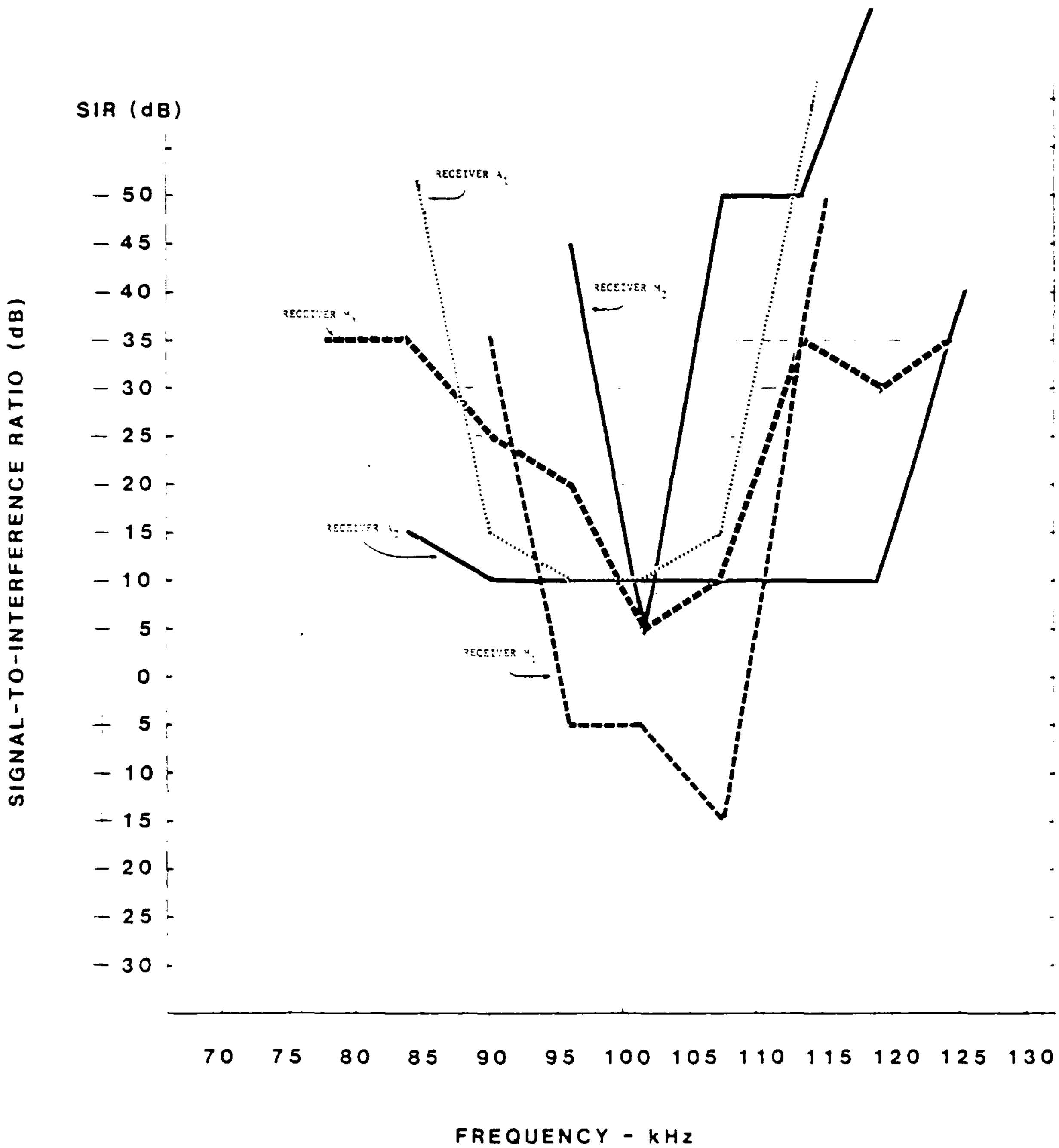

FIGURE 4-2. RESPONSE OF RECEIVERS TO NEAR-SYNCHRONOUS CWI

In an attempt to understand the frequency sensitivity of the measured receiver performance, the frequency was readjusted to a near-synchronous frequency of approximately 97 kHz. At this frequency the sensitivity of the receiver to interference was typical of other receivers.

Next, the frequency was adjusted to a near-synchronous frequency of approximately 96.5 kHz. Again, typical performance was observed. Upon returning to the original 96 kHz near-synchronous frequency, the original measurement could not be repeated, and the measured effect of interference was observed to be typical of other receivers tested. Further, it was no longer possible to repeat the original 96 kHz measurement.

In a further attempt to understand the receiver's performance, the skywave interference measurement data obtained during the Coast Guard's "5-day receiver test" was examined. These data showed a very large affect from simulated skywave interference, the time difference being shifted as much as 0.82 microseconds. This performance is indicative of narrow RF bandwidth on the part of the receiver. Time constraints prevented further investigation of receiver M_2 behavior.

4.3.2 Critique of Marine Receiver M_1 Performance

The EECEN data for receiver M_1 showed a very high sensitivity to near-synchronous CWI (Figure 4-3). To verify the original EECEN measurement, several points were spot checked. These checks validated the original data.

4.3.3 Decreased Sensitivity at 113 kHz

The DOT/TSC Test Plan required that all fixed, manually-tuned and automatic notch filters be removed from the 70 kHz - 130 kHz band.* During the validation test series, it was determined that notch filters remained operational in several receivers during both the original EECEN tests and the later TSC validation tests.

Receiver A_1 was equipped with four fixed and four automatic notches. The four automatic notches were disabled using a procedure provided by the manufacturer. Subsequent discussions with the manufacturer indicated that the notch disabling procedure resulted in movement of two of the notches to positions at 50 kHz and two to positions at 114 kHz. Contrary to plan, the four fixed notches were not disabled; these had been adjusted at the factory to 88.0, 113.0, 87.3 and 123.0 kHz.

*Receivers were ordered with these stipulations. Initial data analysis indicated decreased sensitivity to interference at 113 kHz for several receivers and this was verified during the validation tests.

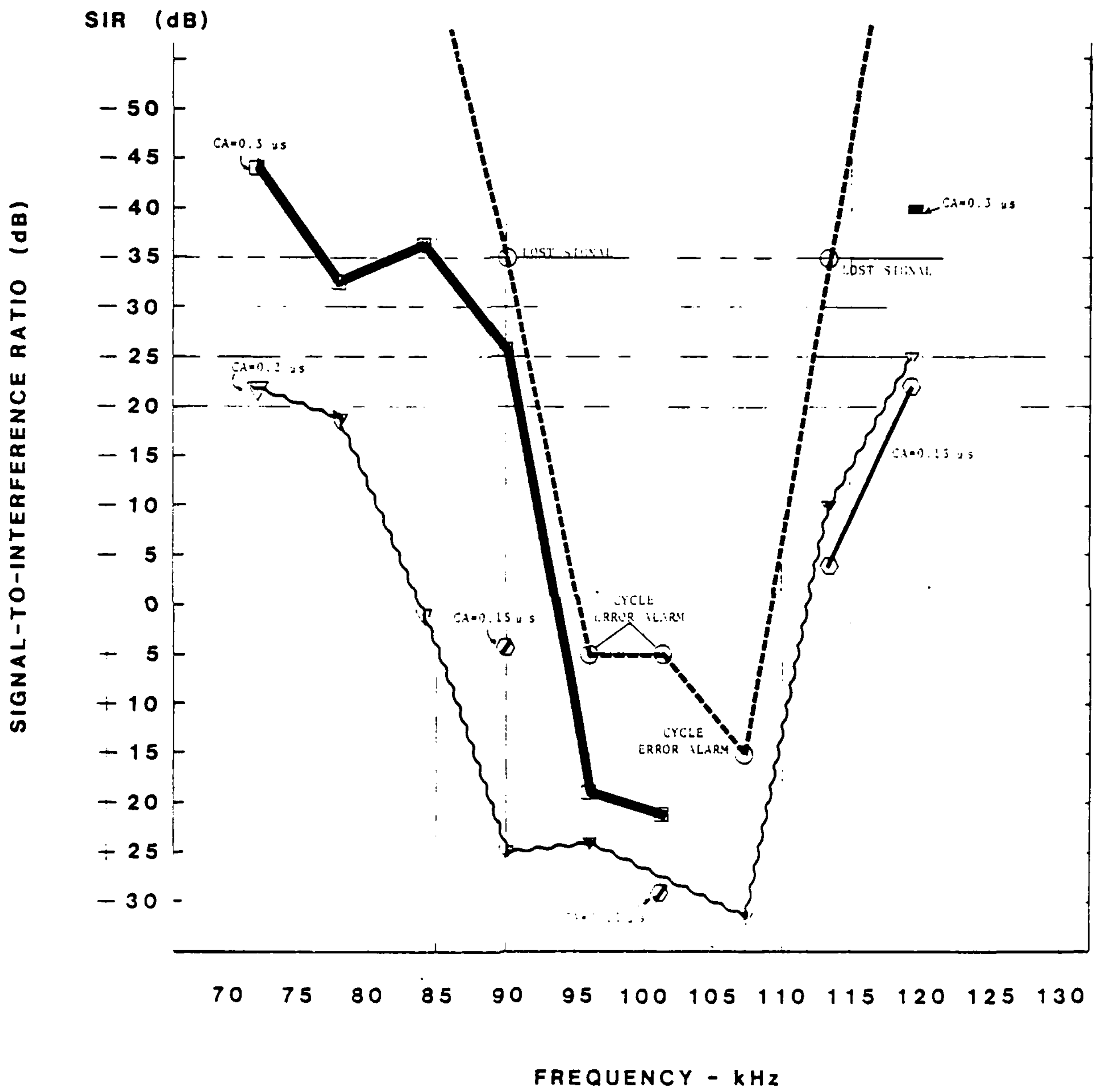

FIGURE 4-3. RECEIVER M_1 RESPONSE TO NEAR-SYNCHRONOUS CWI

The notches at 113 and 114 kHz appear to have had an effect on data taken at 113 kHz, see Figure 4-4 and Table 4-2. The effect of the notches at 113 and 114 kHz are evident in the three curves for CWI and NB FSK in the region of SIR -10 dB to -25 dB versus frequency 110 kHz. Comparing points for these three curves at 110 kHz with points at 90 kHz the following differences are shown in Table 4-3:

TABLE 4-2. COMPARISON OF LIMITING SIRS - RECEIVER A_1

	Frequency kHz					
	85	90	95	105	110	115
Near-synchronous CWI	-45 dB	-15 dB	-12 dB	-13 dB	-36 dB	-55 dB
Non-synchronous CWI	-50 dB	-21 dB	-12 dB	-10 dB	-34 dB	-55 dB
NB FSK	-12 dB	- 5 dB	- 3 dB	- 8 dB	-20 dB	-25 dB
WB FSK	-14 dB	- 5 dB	- 2 dB	- 3 dB	- 5 dB	-10dB

TABLE 4-3. COMPARISON OF RELATIVE SIRS - RECEIVER A_1

	Δ SIR 110 versus 90 kHz	Δ SIR 115 versus 85 kHz
Near-synchronous CWI	21 dB	10 dB
Non-synchronous CWI	13 dB	5 dB
NB FSK	15 dB	13 dB
WB FSK	± 0 dB	-4 dB

Airborne receiver A_2 was equipped with nine notches. These had been factory set to 73.6, 77, 88, 113.2, 115.3, 119.85, 124, 128.25 and 134.9 kHz. As with receiver A_1, the notch at 113.2 kHz appears to have affected the data taken at 113 kHz.

Marine receiver M_2 was equipped with four automatic and several optional fixed notch filters. During the EECEN tests, the automatic notches were disabled. Two fixed notches, tuned to 88 and 113 kHz, were present. Again, the 113 kHz data were affected, although to a much lesser extent and then only the NB FSK data disclosed a meaningful displacement.

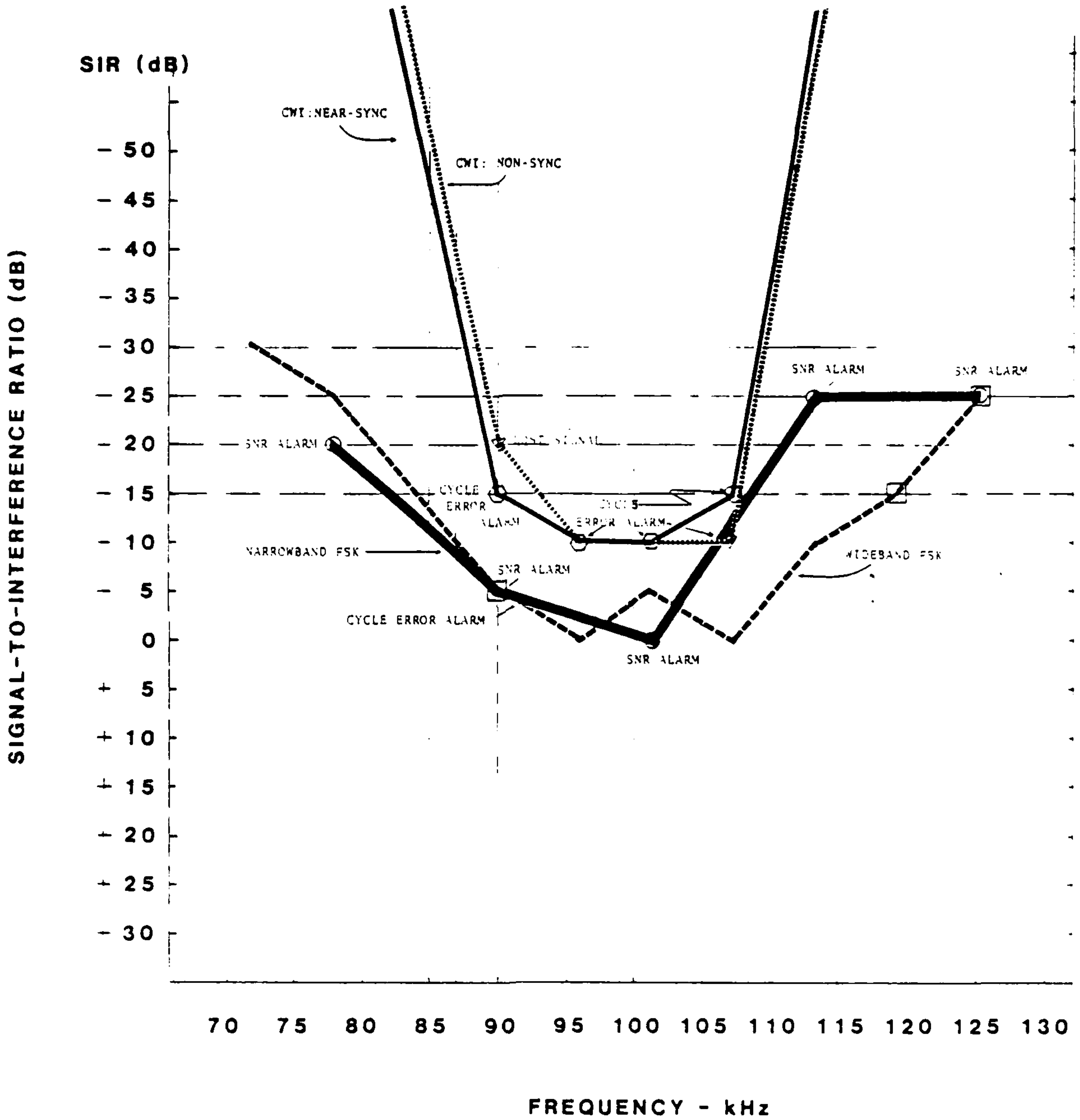

FIGURE 4-4. COMPARISON OF RESPONSE OF RECEIVER A_1 TO FOUR TYPES OF INTERFERENCE

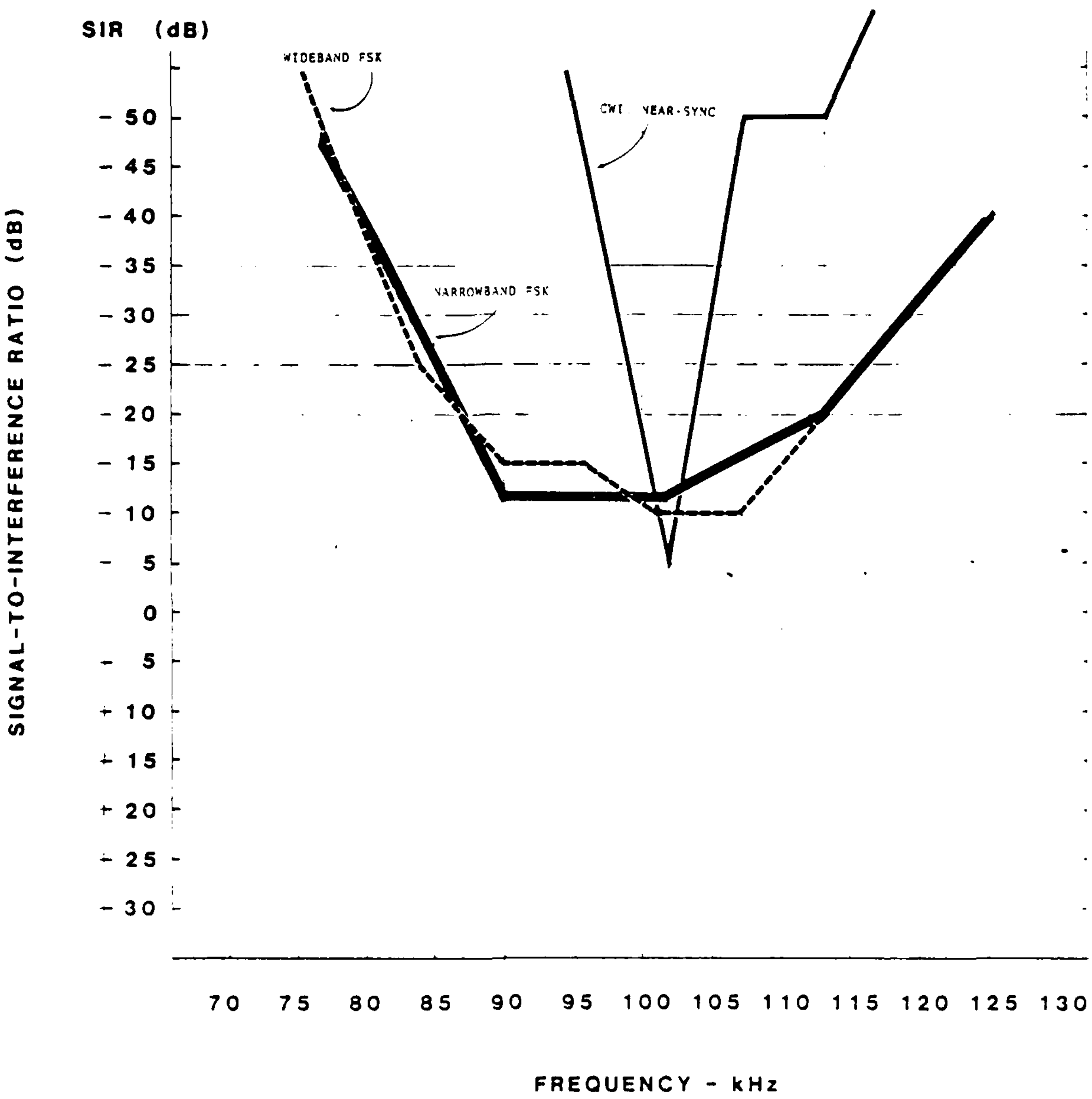

FIGURE 4-5. COMPARISON OF RESPONSE OF RECEIVER M_2 TO THREE TYPES OF INTERFERENCE

Marine receiver M_1 was equipped with four automatic notch filters. These were successfully tuned out of the LORAN-C band during the tests. The relative symmetry of the data points at the 87 and 113 kHz frequencies may be observed in Figure 4-6.

Marine receiver M_3 is typically offered for sale with optional notches. However, none were present at the time of the EECEN tests. Receiver M_3 did contain a special filter with reject frequencies associated with the Decca Navigator System, rejecting interference in the region of 76 and 113 kHz.

This filter reduced the effect of the interference imposed at 113 kHz. In Figure 4-7 and Table 4-4 the data show a 5 to 10 dB improved ability to withstand interference at 113 kHz as compared with interference emitted at 87 kHz.

TABLE 4-4. COMPARISON OF SIRS - FILTERS NEAR 87 AND 113 kHz - RECEIVER M_3

	Δ SIR versus Frequency	
	87 kHz	113 kHz
Near-synchronous CWI	-30 dB	-35 dB
Non-synchronous CWI	-25 dB	-35 dB
NB FSK	-22 dB	-30 dB
WB FSK	-27 dB	-35 dB

The asymmetry of the interference sensitivity data, with respect to the 100 kHz center frequency, is assumed to be caused by rejection (due to notches) by four of the five test receivers of interference at frequencies near 113 kHz. As a result, the recommended protection criteria boundary curves in Section 5 were adjusted downward at 113 kHz to provide symmetry about the central frequency of 100 kHz.

4.4 LIMITATIONS OF DATA

An examination of the TD combined accuracy data computed by EECEN during the data-taking phase of the test showed that for small values of jitter, the value did not monotonically increase with decreasing SIR. In an attempt to understand this phenomena, two aspects of the measurements were considered. The first was resolution of the displayed time difference readings. The second aspect was the jitter to be expected in simulated atmospheric noise of an intensity necessary to produce a signal-to-noise ratio of -10 dB.

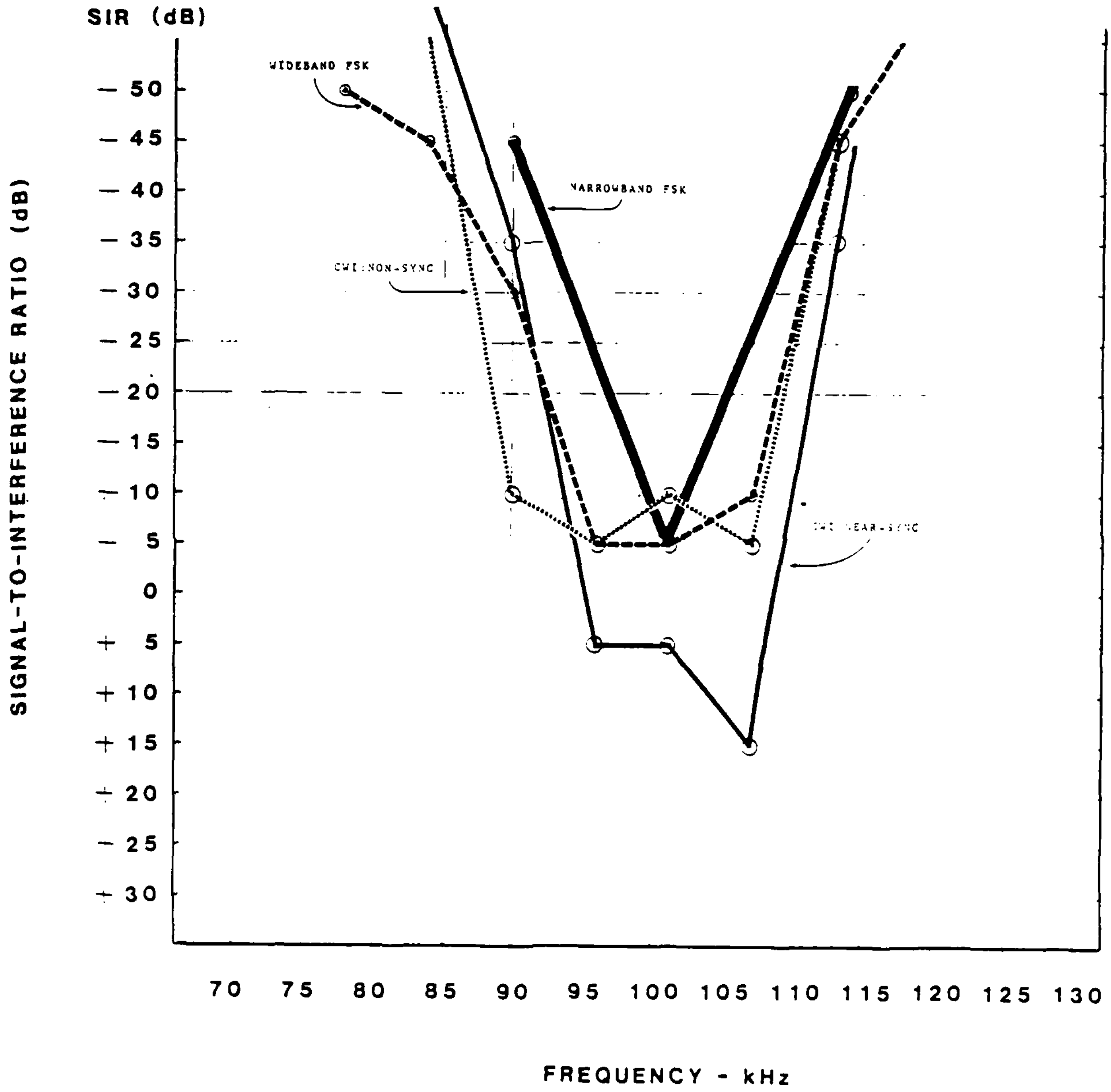

FIGURE 4-6. COMPARISON OF RESPONSE OF RECEIVER M_1 TO FOUR TYPES OF INTERFERENCE

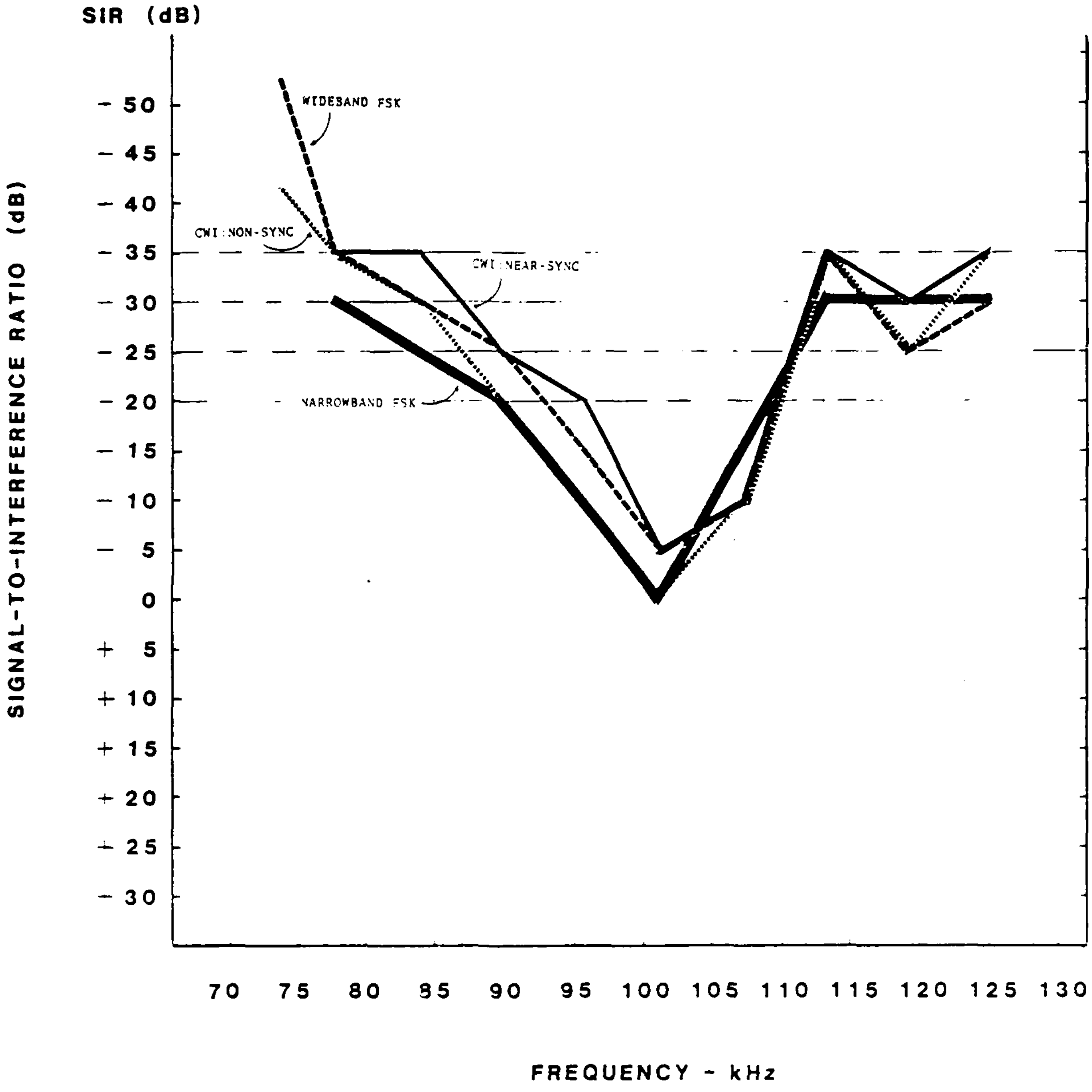

FIGURE 4-7. COMPARISON OF RESPONSE OF RECEIVER M_3 TO FOUR TYPES OF INTERFERENCE

4.4.1 LORAN-C Receiver Resolution

Several of the receivers tested provided TD outputs with a resolution of 0.1 microsecond. Examination of the raw data showed that in some cases these receivers held a constant 0.1 microsecond TD value throughout the 300-second interval of measurement, while in other cases, perhaps due to a slight change in the mean time difference error (MTDE), the output would jump (dither) by ± 0.1 microsecond. In those cases where the output dithered by ± 0.1 microsecond, the TD CA value was dramatically increased. It was concluded that TD CA values of less than 0.1 microsecond could be biased as much as 0.1 microsecond by resolution of the display.

4.4.2 LORAN-C Receiver Jitter

The interference measurements were made while the receiver was subjected to a 'background' noise of -10 dB 'atmospheric', produced by the atmospheric noise simulator of the LRTC II. Measurements derived using receiver M_3 equate a -10 dB LRTC II atmospheric noise level to a 0 dB Gaussian noise level. A GRI of 9960 and a 0 dB Gaussian signal-to-noise ratio (SNR) yielded an expected jitter in the range of 0.073 to 0.103 microseconds for a receiver with a time constant of 2.2 seconds (typical of the two airborne receivers), while an 8 second time constant (typical of a marine set) will yield a jitter of 0.038 to 0.053 microseconds. Thus, atmospheric noise can affect the CA readings in a random fashion until the applied interference causes the measured CA to exceed either 0.05 or 0.1 microseconds, depending upon receiver type.

It was concluded that TD CA values of less than approximately 0.1 microsecond were strongly affected by the measurement technique, and changes in TD CA in this range were not necessarily indicative of the effects of interfering signals.

4.4.3 Change to Original Test Plan

The original test plan called for the interference tests to be accomplished at decreasing Signal-to-Interference ratios until a point where the TD CA was greater than or equal to 0.3 microsecond. During the testing, a CA value of 0.3 microsecond was seldom realized, as most receivers indicated a flag condition of either BLINK, CYCLE or low SNR at values of CA well below 0.3 microsecond. This is indicated in Figures 4-1, 4-3, 4-8, and 4-9.

For purposes of analyzing the data, either a TD CA value of 0.3 microsecond or excitation of a receiver alarm, whichever was experienced first, was used as the limit of tracking. It was assumed that an operator would consider the TD data unusable in the presence of a receiver alarm even though the system might continue to track. The receiver sensitivity curves and minimum performance curves appearing in sections 4 and 5 are plotted to reflect the TD CA boundary of 0.3 microsecond and/or a receiver flag condition.

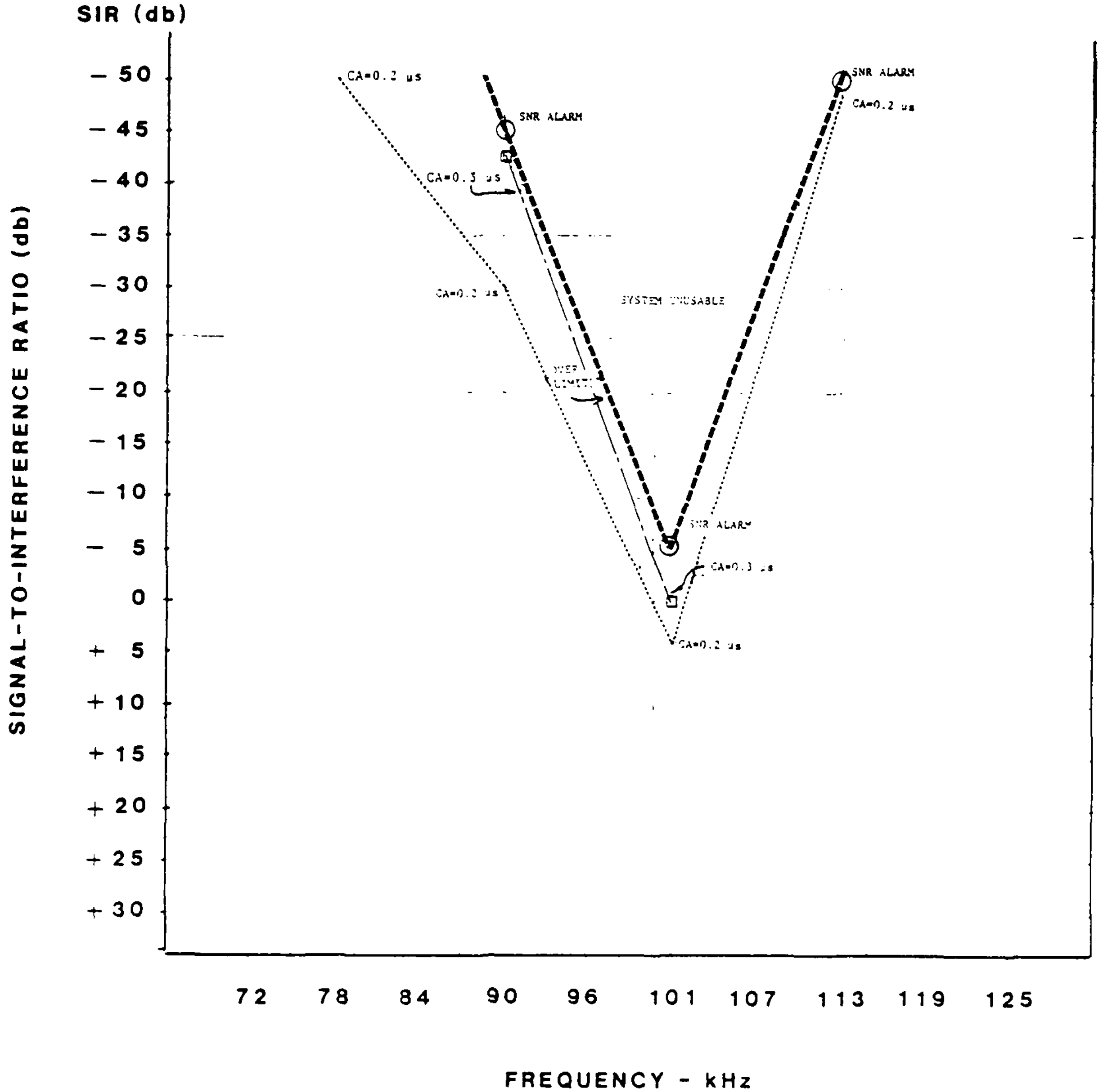

FIGURE 4-8. RECEIVER M_1 RESPONSE TO NARROWBAND FSK INTERFERENCE

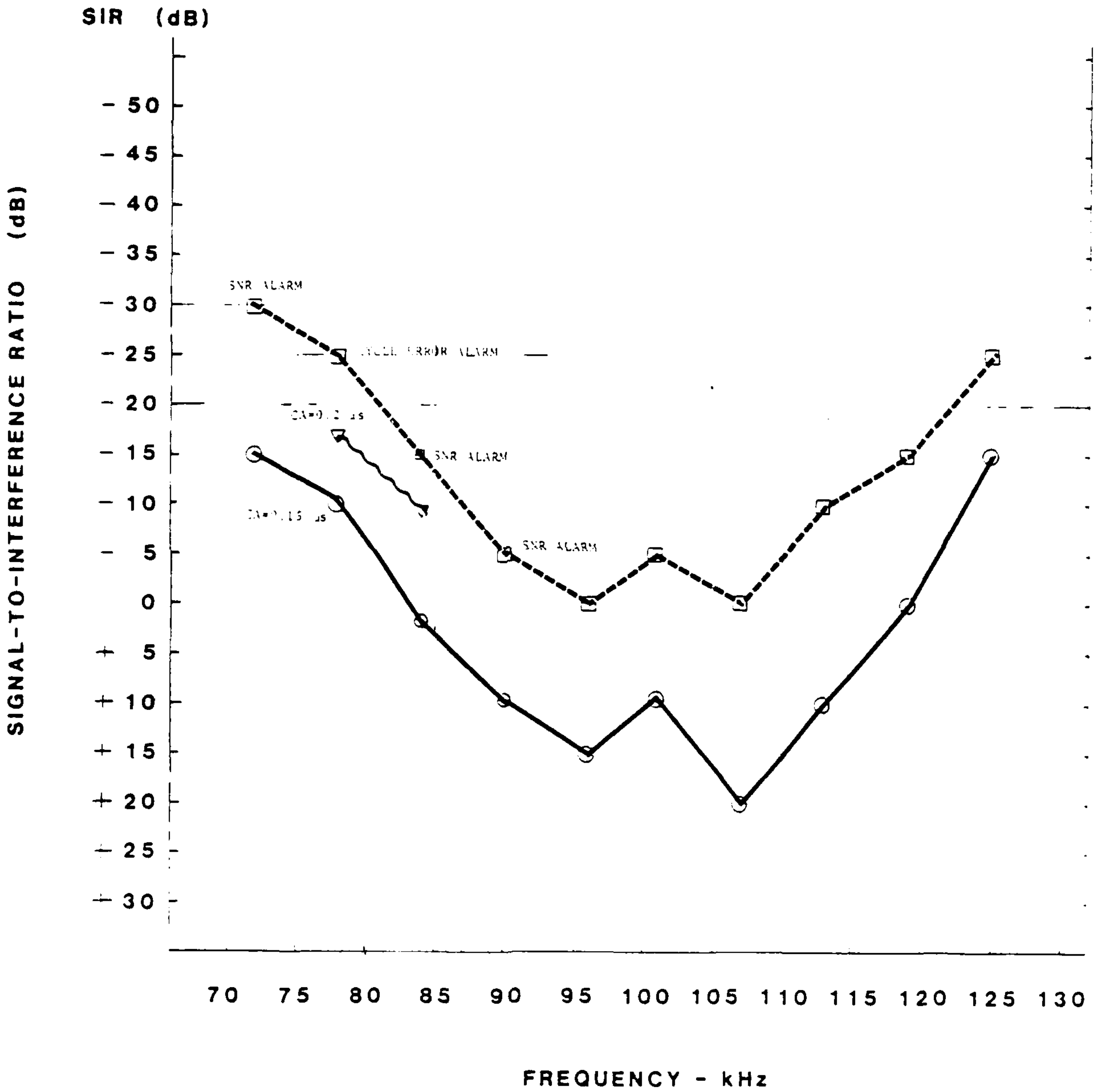

FIGURE 4-9. RECEIVER A_1 RESPONSE TO WIDEBAND FSK INTERFERENCE

4.4.4 Wideband FSK Near-Synchronous and Narrowband FSK Non-Synchronous Tests

The DOT/TSC Test Plan utilized by EECEN originally intended that receiver tracking tests would include evaluation of the five receivers under all combinations of near-synchronous and non-synchronous conditions of interference. However, the actual testing did not include evaluation of receiver performance in the presence of *near-synchronous wideband FSK* or *non-synchronous narrowband FSK* interference due to time limitations in the availability of the LRTC II.

The simulated wideband FSK interference spectrum spanned approximately 3 kHz, or roughly 600 LORAN-C signal spectral lines. While it was possible to consider each one of the 10 lines which *comprise the signal to be either a near- synchronous or non-synchronous* CW interferer, the true effect of the interference was that of energy fairly uniformly distributed over a 3 kHz bandwidth. Thus, it was felt that the characterization of wideband FSK as either near-synchronous or non-synchronous was not meaningful. For this reason, a single classification of "Wideband Interference" was adopted.

A similar consideration held for narrowband FSK interference. In this case, however, the spectrum was narrow enough to warrant additional testing. For this reason, a test was performed using receiver M_3 to determine whether or not there was a significant difference between the two cases. Figure 4-10 and Figure 4-11 present the receiver alarm curves. If the two sets of curves are superimposed, they are seen to be almost perfectly congruent. Based on this evaluation, narrowband FSK interference protection recommendations were not identified as being either near-synchronous or non-synchronous.

4.4.5. Acquisition Tests

The acquisition tests were conducted in the presence of near-synchronous narrowband FSK interference, the most difficult situation for a receiver to overcome. For these tests the signal-to-noise ratio of -10 dB utilized for the tracking tests was improved to a SNR value of 0 dB. This change was made to assure a high probability of correct cycle selection before introduction of any RF interference.

It is noted that a signal-to-noise ratio of -10 dB is the specified lowest SNR at which most receivers will correctly acquire LORAN-C signals. Improving the ratio assured that the variations in measured receiver acquisition performance could be attributed to the imposed interference.

Figure 4-12 presents curves for three receivers. The threshold of interference-acceptability was set at 6 minutes. An interference condition which prevented a receiver from correctly acquiring the third cycle within 6 minutes of system turn on was used as the limit point.

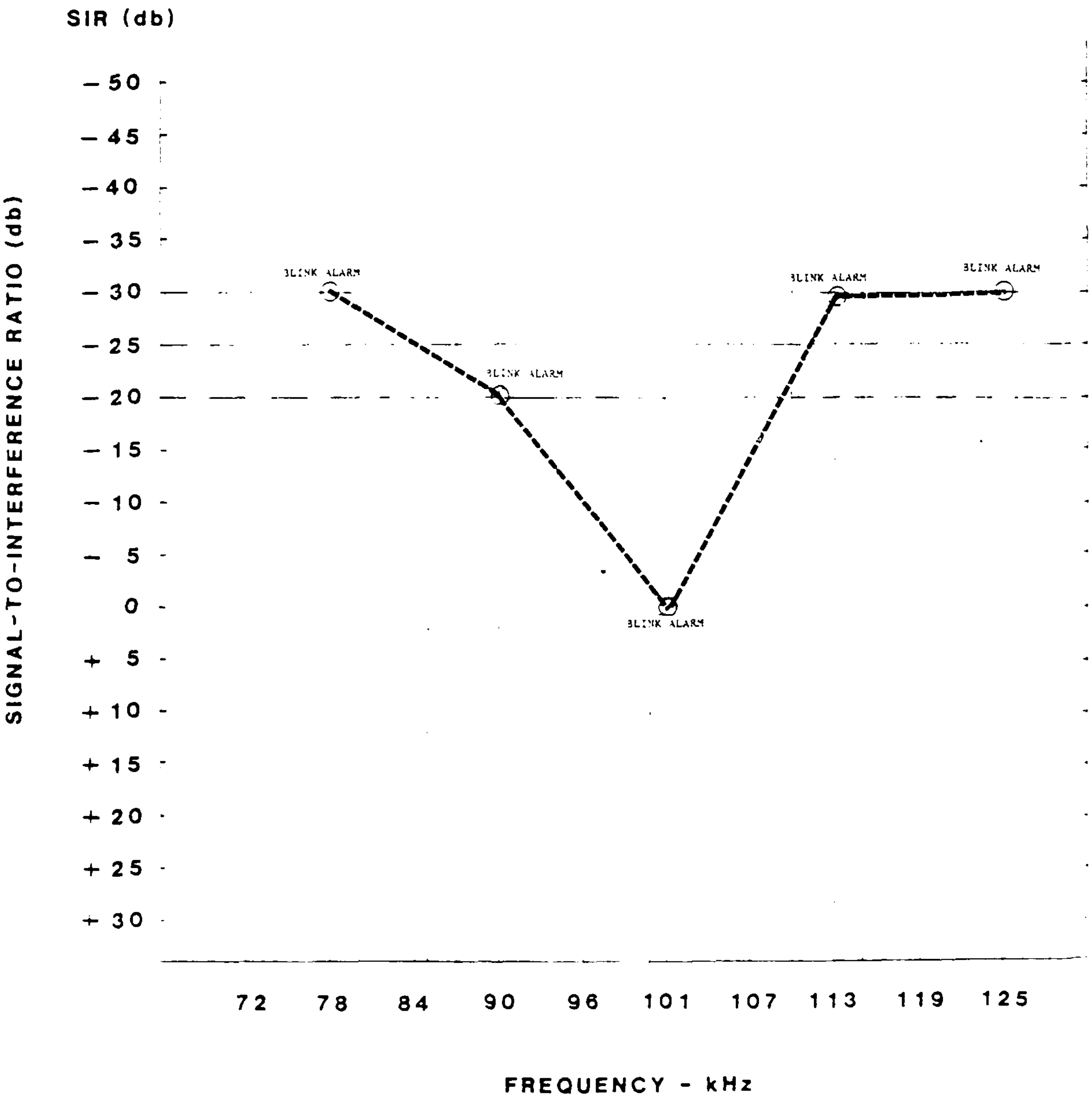

FIGURE 4-10. RECEIVER M_3 RESPONSE TO NARROWBAND FSK NEAR-SYNCHRONOUS INTERFERENCE

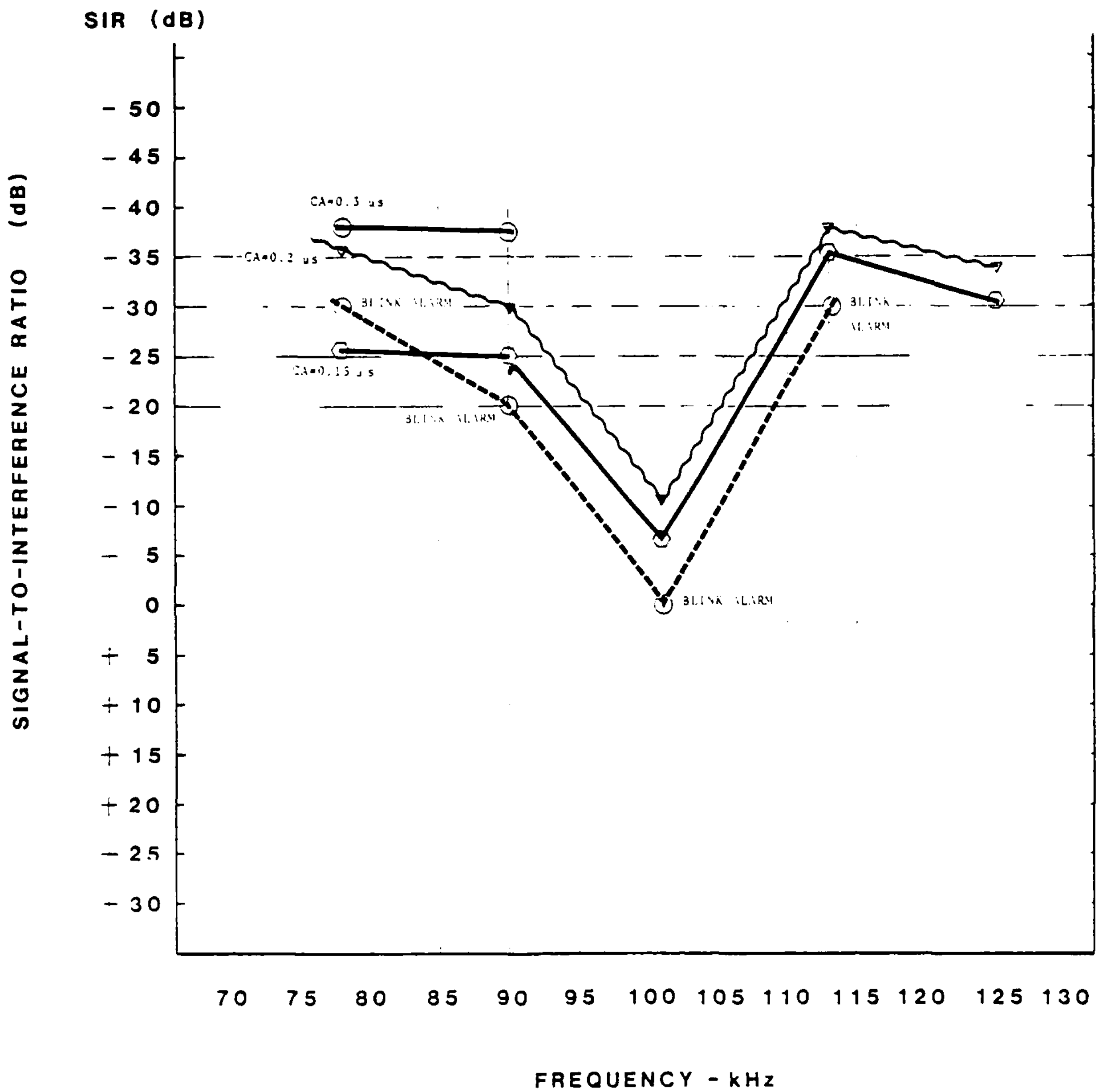

FIGURE 4-11. RECEIVER M_3 RESPONSE TO NARROWBAND FSK NON-SYNCHRONOUS INTERFERENCE

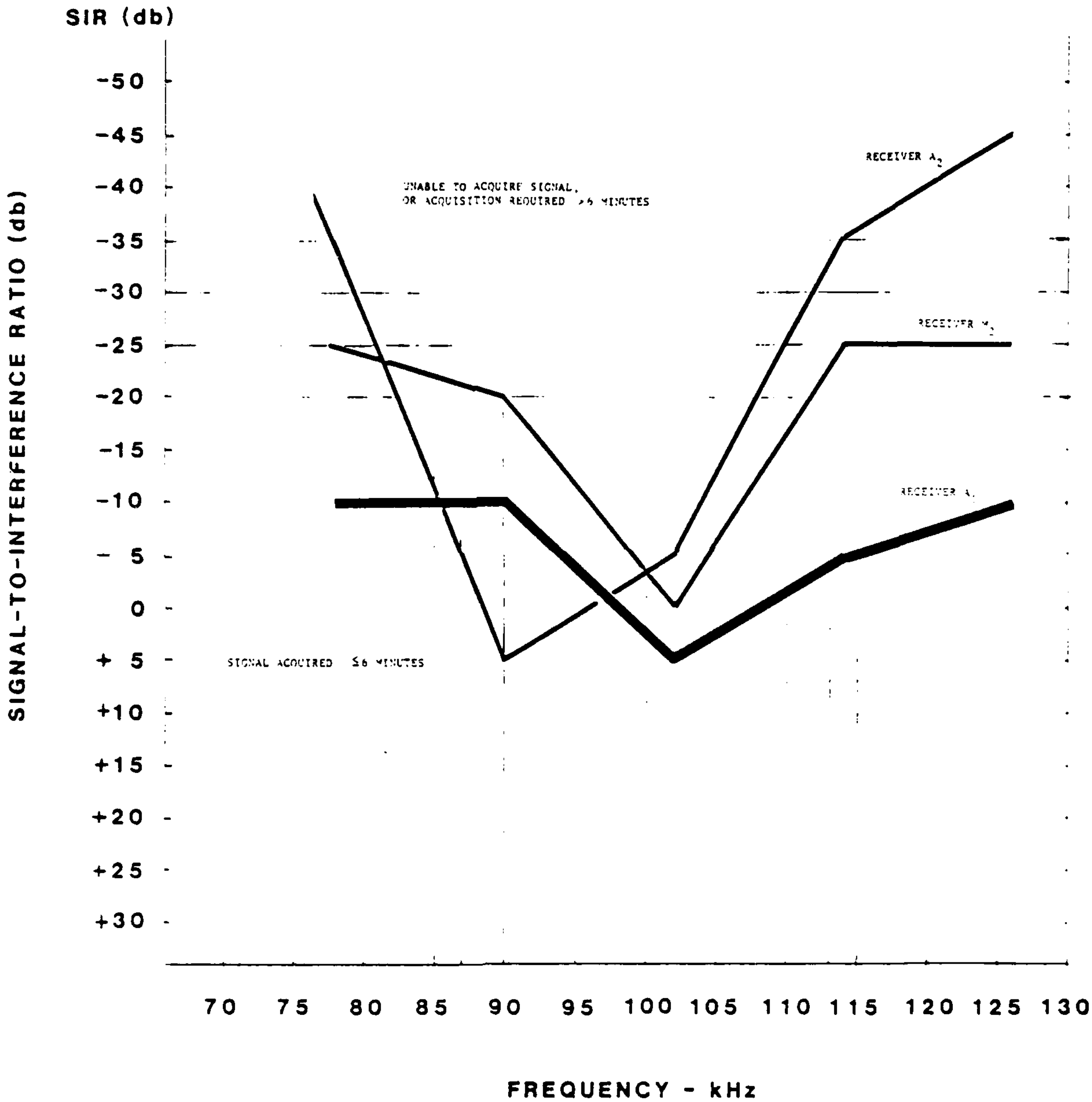

FIGURE 4-12. EVALUATION OF THE LIMITS OF ACQUISITION CAPABILITY - NARROWBAND FSK INTERFERENCE

5. RESULTS

5.1 GENERAL

This section presents composite results for each type of interference, recommended protection criteria and concludes with a proposed procedure to analyze the effects of interference on LORAN-C receivers.

5.2 COMPOSITE RESULTS FOR EACH INTERFERENCE TYPE

After completion of all tests, data for receivers was compared for each type of interference. Performance between different receivers varied over a 40 dB range. Some receivers which showed extra sensitivity to one type of interference were less affected by other types. In the previous section, Figure 4-2 was a composite plot of the performance of all five receivers when subjected to near-synchronous CWI. Further study of the data showed that if a limit was placed at the point where the most sensitive receiver had a combined accuracy of 0.3 microsecond or an alarm condition, a symmetrical envelope could be developed. Figure 5-1 is the composite envelope for all receivers for the case of near- synchronous CWI. Figures 5-2 through 5-4 presents composite envelopes for each of the remaining interference types. Tick marks on the vertical axis indicate where some type of alarm was noted. Actual descriptions were omitted to avoid unnecessary detail in the figure.

5.3 MINIMUM PERFORMANCE CURVES

Each of the composite envelopes or curves shown in Figures 5-1 through 5-4 represents a threshold. When the signal to interference ratio is greater than the threshold, all of the receivers performed within acceptable limits. The threshold ratio was chosen as a minimum for acceptable performance.

5.3.1 Continuous Wave Interference Curves

Comparison of receiver performance for near-synchronous versus non-synchronous interference showed that the receivers needed a 5 dB improvement in signal level to achieve normal performance. Minimum performance curves were prepared for each type of continuous wave interference and are presented in Figure 5-5. The format of the curve is that used by the CCIR in Report 915.

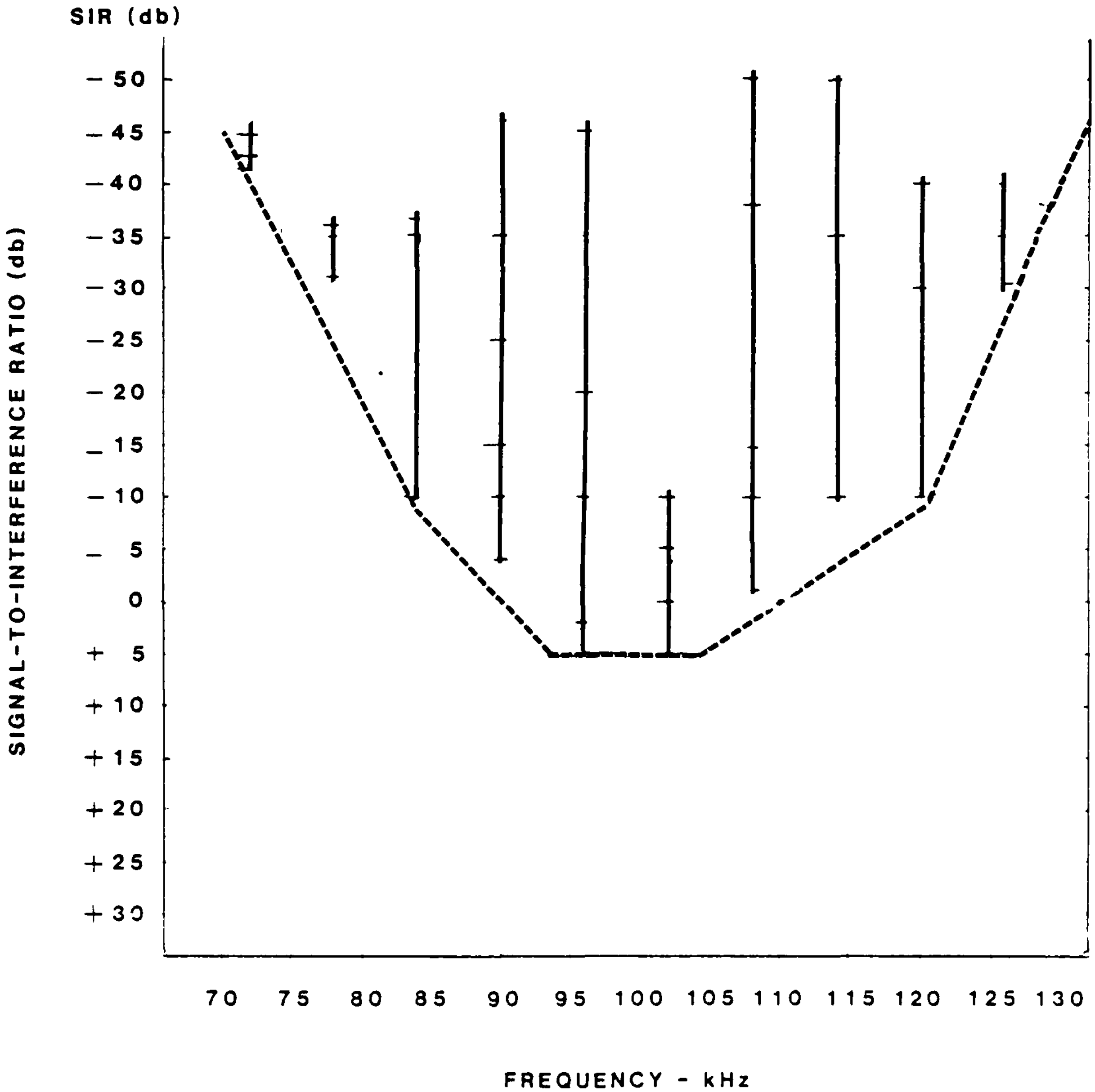

FIGURE 5-1. COMPARISON OF THE RESPONSE OF RECEIVERS TO NEAR-SYNCHRONOUS CWI

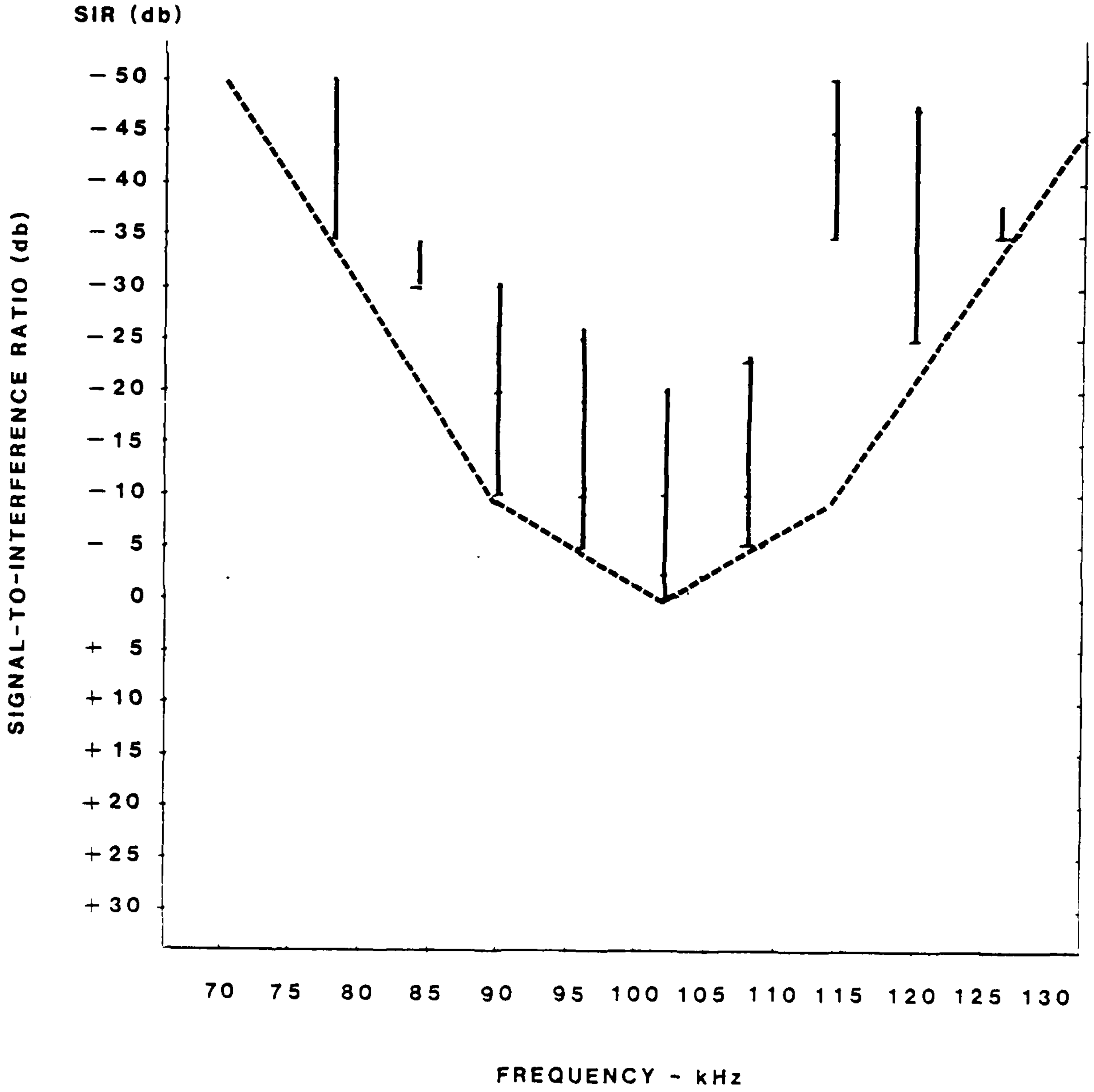

FIGURE 5-2. COMPARISON OF THE RESPONSE OF RECEIVERS TO NON-SYNCHRONOUS CWI

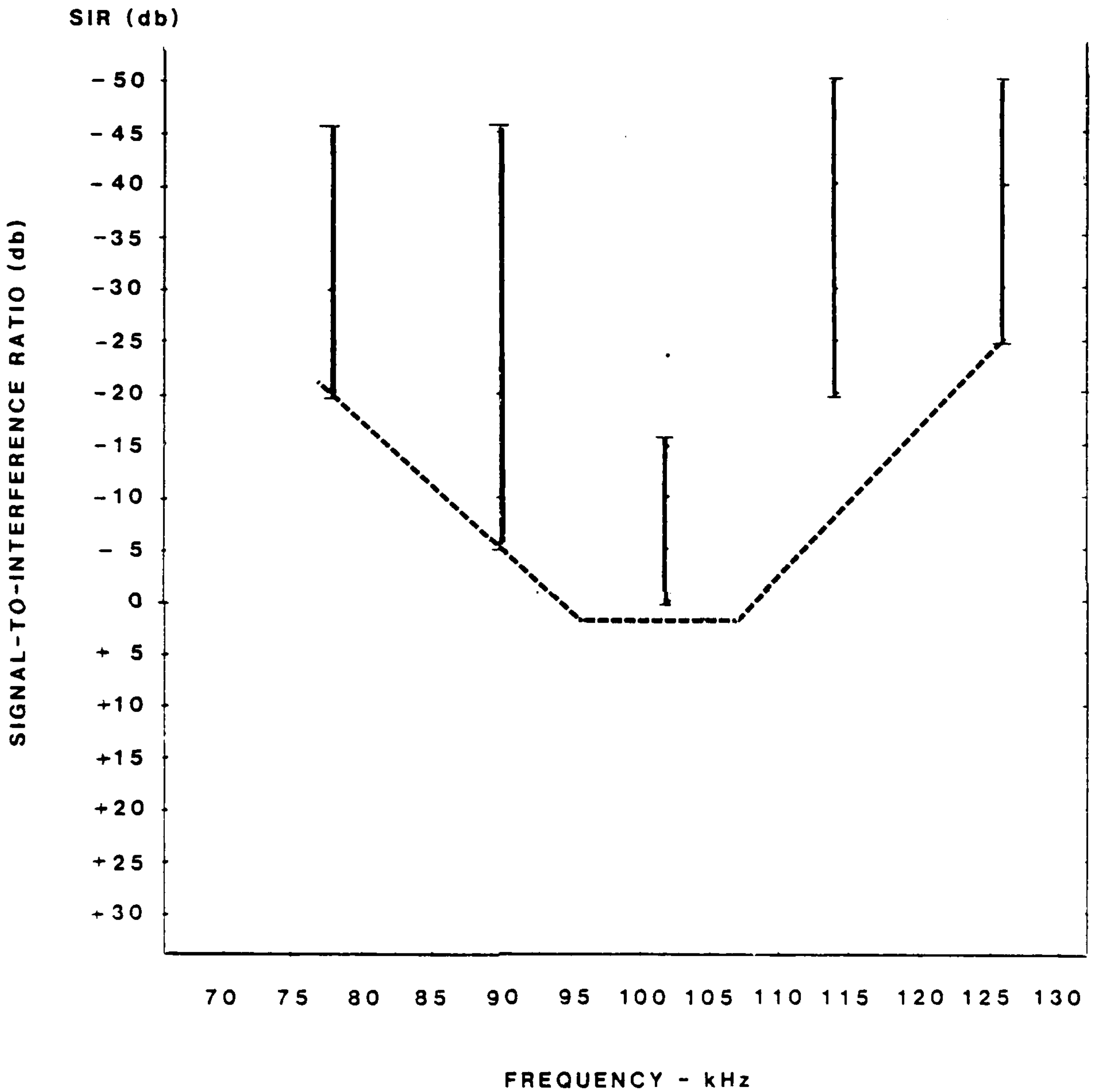

FIGURE 5-3. COMPARISON OF THE RESPONSE OF RECEIVERS TO NARROWBAND FSK INTERFERENCE

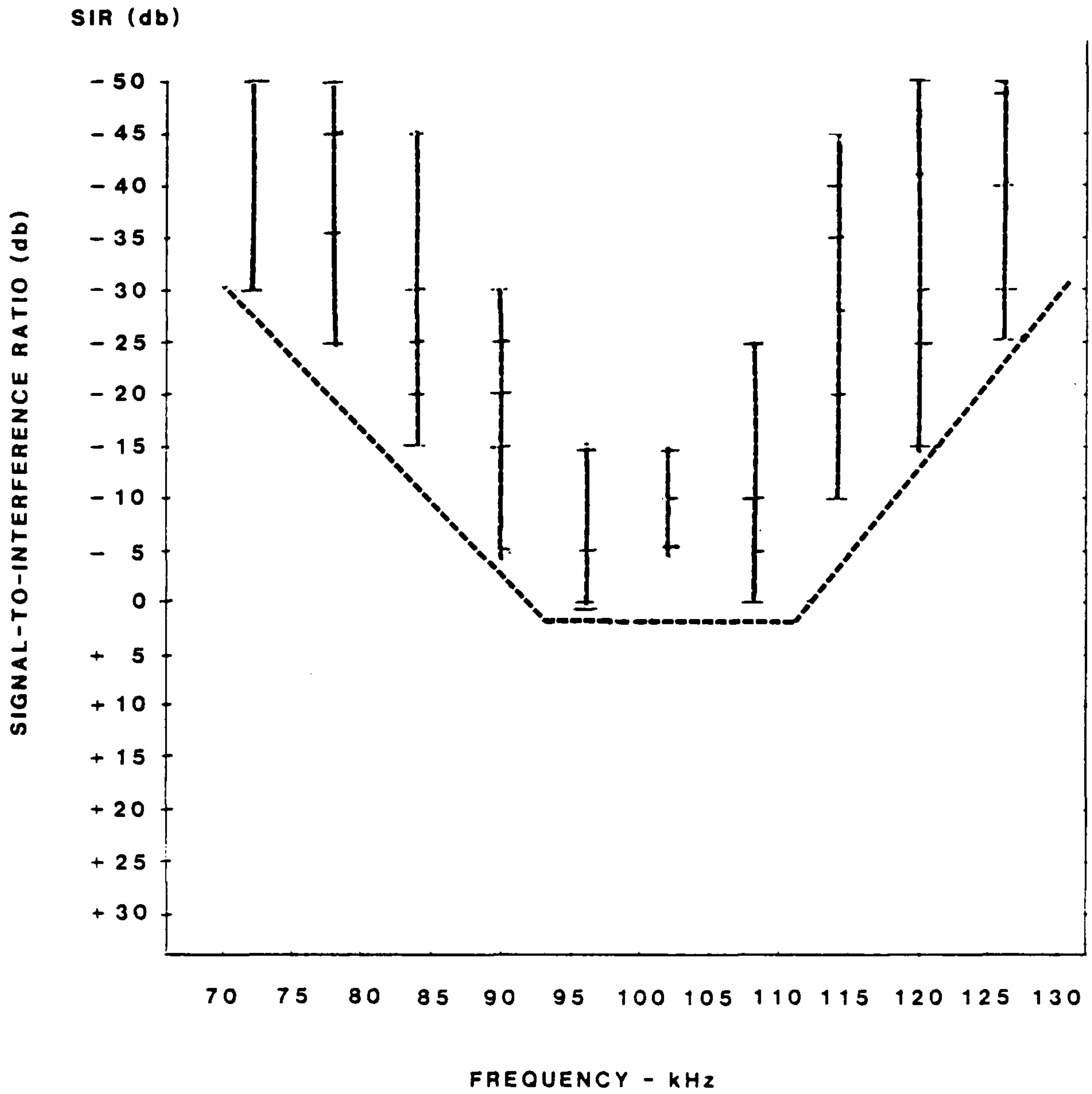

FIGURE 5- 4. COMPARISON OF THE RESPONSE OF RECEIVERS TO WIDEBAND FSK INTERFERENCE

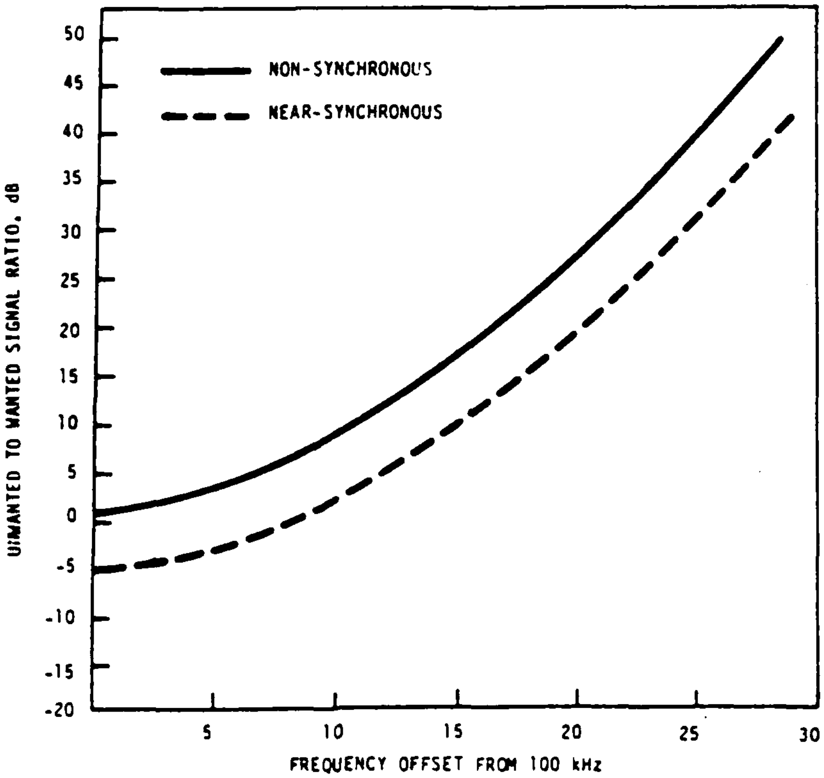

FIGURE 5-5. MINIMUM PERFORMANCE CURVES FOR NEAR AND NON-SYNCHRONOUS CWI

5.3.2 FSK Interference Curves

Examination of all FSK information showed that the required signal to interference ratio for minimum receiver performance was the same for both types of interference except at 113 kHz. As discussed in section 4.3.3, four of the receivers effectively had notches at this frequency and thus were less sensitive to the interference. The fifth receiver was insensitive to both types of FSK interference. Reflecting this analysis, a single curve was produced for FSK interference and is presented in Figure 5-6.

5.4 RECOMMENDED PROTECTION MARGIN

The minimum performance limits presented in Section 5.2 reflect the effect of various types of interference on receiver tracking performance. A protection boundary for LORAN-C receivers must also incorporate allowances for receiver acquisition and variation in atmospheric noise structure.

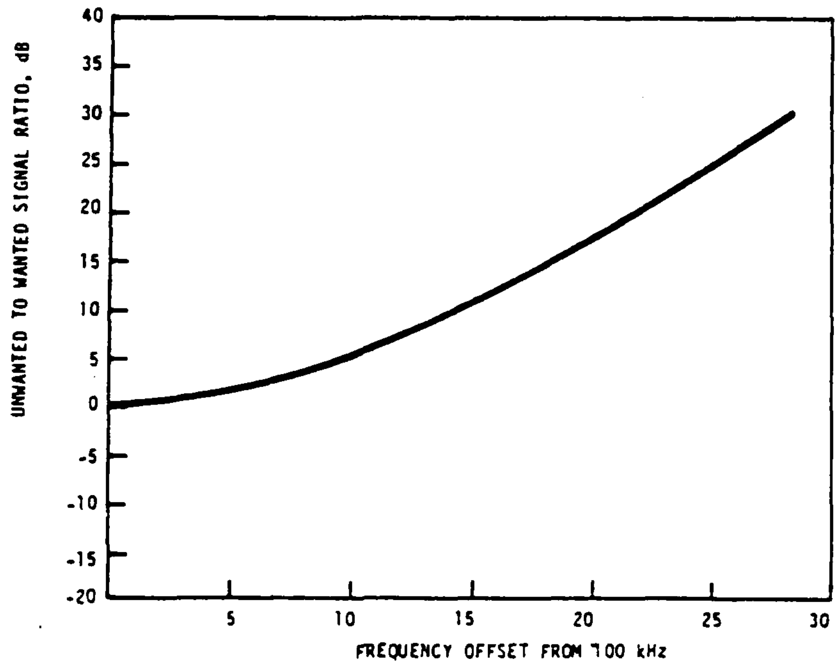

FIGURE 5-6. MINIMUM PERFORMANCE CURVE FOR FSK INTERFERENCE

5.4.1 Receiver Acquisition

Receiver acquisition in the presence of noise is a more difficult task than continued tracking when noise is introduced. The acquisition tests discussed in Section 4.4.5 provided data to establish an additional protection margin. Comparison of the acquisition versus tracking performance of the receivers tested indicated that at least a 5 dB higher SIR was required to correctly acquire a signal than was required to track. The observed limit was smaller than expected. Re-examination of tracking data showed that most receiver failures occurred due to issuing of one of the receiver alarms rather than loss of signal track. The mechanisms which trigger the CYCLE, BLINK AND SNR alarms are related to signal amplitude rather than cycle tracking and reflect a measurement similar to that involved in the cycle identification task. A margin between 5 to 10 dB is desirable for acquisition protection.

5.4.2 Noise Variation

The atmospheric noise source used for the tracking tests was modeled after "tropical" noise. For operating regions other than the tropics, atmospheric noise becomes less impulsive and more Gaussian. The effect of Gaussian noise on LORAN-C receivers is to reduce tracking performance, thus requiring an increase in minimum SIR. During the jitter tests discussed in section 4.4.2, it was determined that a SNR of 0 db Gaussian produced jitter identical to that of -10 dB for the "atmospheric" noise generator of the LRTC II. Identification of noise variation throughout the regions was beyond the scope of this study. An additional protection margin between 5 and 10 dB is desirable to account for variations in background noise conditions.

5.4.3 Recommended Protection Curves

The considerations of signal acquisition and noise suggest an increase in the protection boundary ranging between 10 and 20 dB. A figure of 15 dB was selected. Figures 5-7 and 5-8 present recommended protection curves for the frequency band of 70-130 kHz and incorporate this additional 15 dB protection margin.

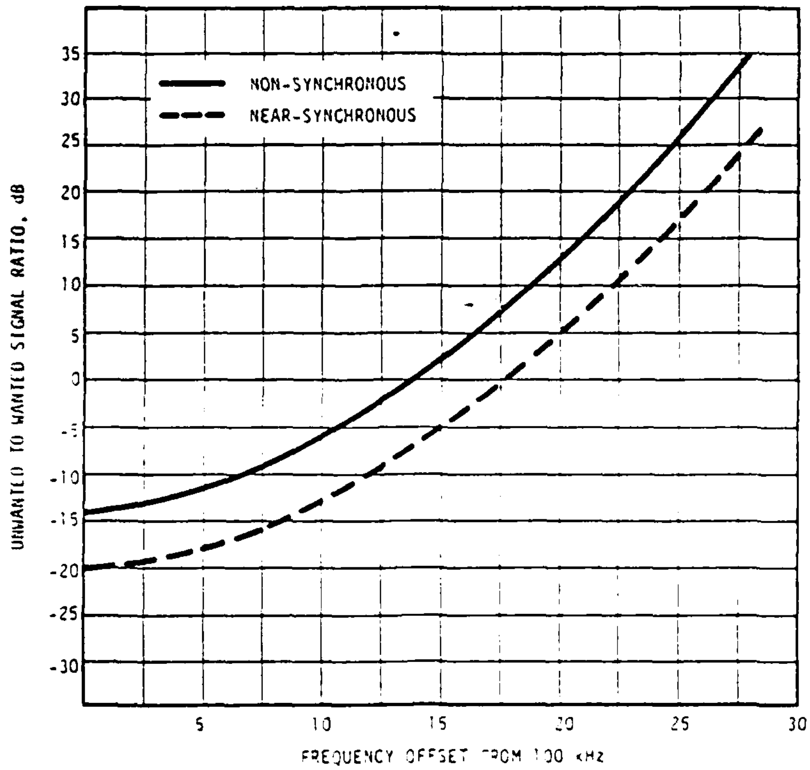

FIGURE 5-7. SUGGESTED PROTECTION BOUNDARY FOR CONTINUOUS WAVE INTERFERENCE

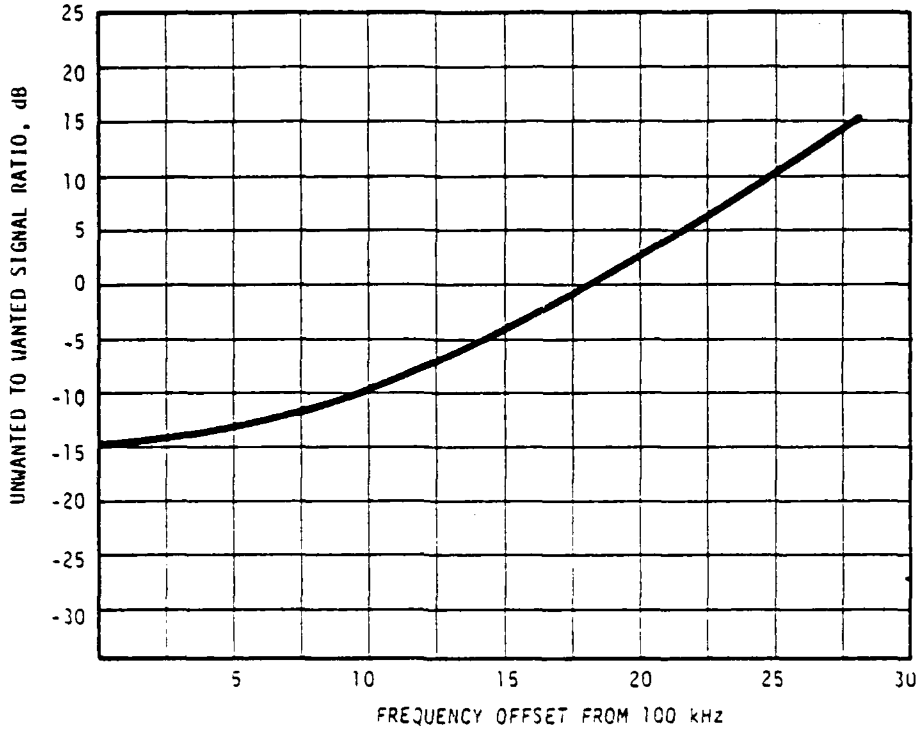

FIGURE 5-8. SUGGESTED PROTECTION BOUNDARY FOR FSK INTERFERENCE

5.5 PROPOSED TECHNIQUE FOR ASSESSING EFFECTS OF MULTIPLE INTERFERENCE

The testing used to develop the Loran-C interference sensitivity curves shown in Section 4 and summarized above, employed a single interfering signal for each of the types of interfering signals tested. This section describes a technique which could be used to assess the overall effect of a multiplicity of interfering signals (more representative of real-world conditions) which vary both in frequency and type. The technique was developed after completion of interference tests and can be verified through future tests.

5.5.1 Assumptions

- Due to the pulse nature of the Loran-C signal, the effect of a multiplicity of interferers on the sampling point will add in a root sum square manner, according to their effective levels during post sampling signal processing.
- The Loran-C receivers subject to protection by this criteria are designed to include at least four notch filters. Two of these filters are located above the Loran-C band in the

frequency range from 110-130 kHz, and two are located below the primary Loran-C band in the frequency range from 70-90 kHz.

- Each of the receiver's notches are assumed to have a 30 dB rejection bandwidth of 100 Hz. That is, frequencies located ± 50 Hz from the center frequency of the notch filter will be reduced by at least 30 dB.

5.5.2 Proposed Procedure

The technique proposed for assessing the effect of multiple interfering signals is accomplished using the following nine steps:

STEP 1

At geographical locations inside the LORAN-C coverage area to be protected, determine the equivalent rms signal level of the weakest LORAN-C pulse train to be tracked at the standard sampling point. This is the effective LORAN-C signal strength.

STEP 2

Using the signal protection margin required for near-synchronous interference at 100 kHz, determine the maximum acceptable interfering signal field strength. This level is assumed to be the maximum, weighted rss interference signal level acceptable to a LORAN-C receiver at the selected location. The near-synchronous level was selected because testing showed this type of interference to be most detrimental to LORAN-C receivers.

STEP 3

For the selected location, identify all interfering signals and characterize them by frequency, intensity and modulation type. The modulation types to be considered are near-synchronous CW, non-synchronous CW, narrowband FSK and wideband FSK.

STEP 4

Reduce all interfering signals levels by the ratio of the sensitivity of the receiver to the type and the frequency of interfering signal, in accordance with the relative effect of interference shown in the protection criteria curves.

STEP 5

Identify the interfering signal in the frequency range from 70-90 kHz which has the greatest effect. If the bandwidth of the signal is less than 100 Hz, reduce its effective intensity by 30 dB under the assumption that the signal would be notched by the receiver.

STEP 6

Repeat step 4 to reduce the amplitude of the remaining largest amplitude signal of

bandwidth less than 100 Hz. (Note: It may be desirable to place both notches on the interfering frequency.)

STEP 7

In certain circumstances, it may be desirable to use the two notches to eliminate a single interferer of bandwidth greater than 100 Hz by placing the two notches side by side. If this appears to be the case, it may be necessary to repeat this interference sensitivity assessment process twice, once notching out two individual narrowband signals and once using both notches to minimize the effect of a single broader band interferer.

STEP 8

Repeat steps 5, 6 and 7 for interfering signals in the frequency band from 110-130 kHz.

STEP 9

Finally, compute the square root of the sum of the squares of the field strengths of the weighted interfering signals to obtain an effective interfering signal level. If this level exceeds the maximum acceptable level computed in step 2, the LORAN-C system performance will be reduced to an unacceptable level.

5.5.3 Example of the Use of Protection Curves

Step 1. Assume that the LORAN-C signal strength is 1.0 millivolts/meter (mV/m).

Step 2. From Figure 5-9, the protection required at 100 kHz against near- synchronous CW interfering signals is 20 dB, or a voltage ratio of 10:1. Thus, for a 1.0 mV/m LORAN-C signal, the maximum weighted rss interference level is 0.1 mV/m. Figure 5-10 presents the example for FSK interference.

Step 3 The assumed interference sources are shown in Table 5-1 below.

TABLE 5-1. DATA FOR EXAMPLE

Interference	Frequency	Type of Interference	Level
#1	113 kHz	Near-synchronous CWI	7 mV/m
#2	117 kHz	NB FSK	7 mV/m
#3	87 kHz	Near-synchronous CWI	16 mV/m
#4	80 kHz	Non-synchronous CWI	1.4 mV/m
#5	96 kHz	NB FSK	0.3 mV/m

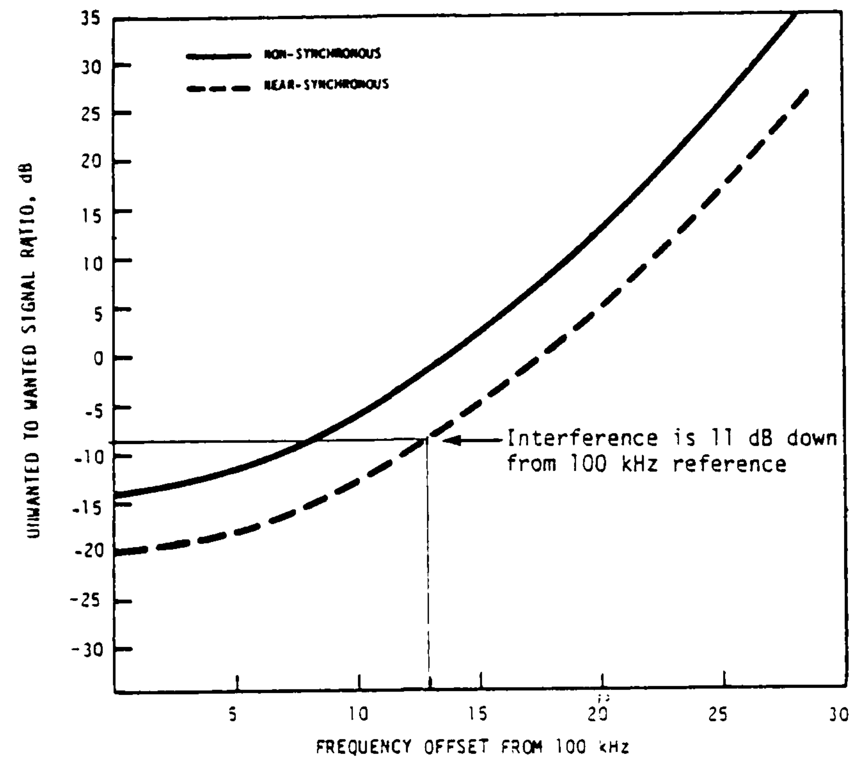

FIGURE 5-9. EXAMPLE OF INTERFERENCE PROBLEM FOR CONTINUOUS WAVE INTERFERENCE

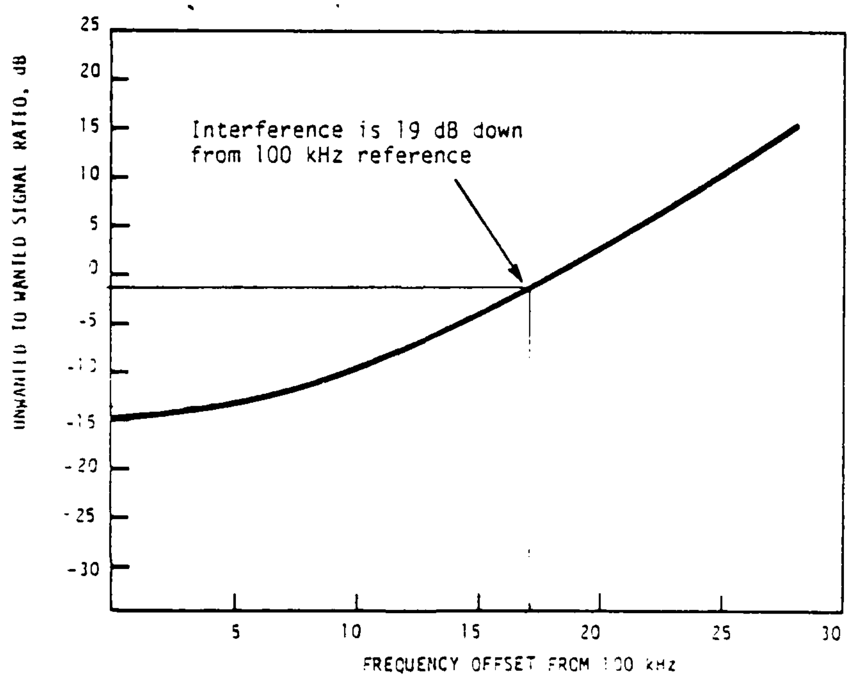

FIGURE 5-10. EXAMPLE OF INTERFERENCE PROBLEM FOR FSK INTERFERENCE

Steps 4 through 6 are considered for three examples. Table 5-2 summarizes the calculations. The first four columns list the characteristics of the assumed interference sources. Columns five to eight show the reduction of the effect of the interference due to the type of modulation, frequency of the signal, and the application of notch filters. The last column lists the final effective level of each interference, and the total effective rss level for all assumed interfering signals.

Example A in Table 5-2 shows an acceptable situation of 0.068 millivolts/meter rss, compared to the limit of 0.1 millivolts/meter rss calculated in step 2. Note that two notches were placed on interferer #3.

In example B, a fourth interfering signal of relatively low level is added to the signals assumed in example A. Due to the low level of the new signal when compared to interferer #3, both notches are again placed on interferer #3, leaving interferer #4 unnotched The equivalent level of the interference is still acceptable at 0.076 millivolts/meter rss.

Example C in Table 5-2 shows the effect of a single relatively low level interferer when it occurs in the band from 90-110 kHz. As most receivers do not permit notch filters to be tuned inside this band, the assumed 96 kHz NB FSK interfering signal only benefits from the 6 dB relative sensitivity protection of the receiver against NB FSK modulation. The net effect of this single interferer is an effective interference level of 0.15 millivolts/meter, 50 microvolts/meter above the limit of 0.1 millivolts/meter.

TABLE 5-2. PROTECTION BOUNDARY CURVE DATA

Interference	Interference Characteristics: Nominal Frequency kHz	Type	Level mV/m	Relative Receiver Sensitivity dB (v. ratio)	Reduction Effects of Notch Filters: Effective Signal Level mV/m	After Notch 1 30 dB (31.64) mV/m	After Notch 2 30 dB (31.64) mV/m	Final Effective Level mV/m
EXAMPLE A								
#1	113	CWI (Near)	7	11 (3.54:1)	1.98	.063		.063
#2	117	NB FSK	7	19 (8.9:1)	.79		.025	.025
#3	87	CWI (Near)	16	11 (3.54:1)	4.52	.143	.0045	.0045
								0.068 rss
EXAMPLE B								
#1	113	CWI (Near)	7	11 (3.54:1)	1.98	063		.063
#2	117	NB FSK	7	19 (8.9:1)	.79		.025	.025
#3	87	CWI (Near)	16	11 (3.54:1)	4.52	.143	.0045	.0045
#4	80	CWI (Non)	1.4	32 (40:1)	.035			.035
								0.076 rss
EXAMPLE C								
#5	96 kHz	NB FSK	.3	6 (2:1)	.15			.15 rss

CWI — Continuous Wave Interference
(Near) — Near-Synchronous
(Non) — Non-Synchronous
NB — Narrowband
FSK — Frequency Shift Keyed
rss — Square root of the sum of the square

All ratios stated as dB (voltage ratio)

6. CONCLUSIONS

The test program conducted at the EECEN provided a data base for the establishment of interference protection boundaries. Basic assumptions regarding receiver performance proved sound. As with any test program where only a sample of products is tested, appropriate care should be exercised when the results are extended to other conditions.

Step response tests showed that the receiver tracking bandwidths varied between 0.01 Hz for marine receivers to 0.07 Hz for avionics receivers. These results provide support for the 1.0 Hz spectral spacing between Loran-C and synchronous interference proposed in the U.S. Government amendment to CCIR Report 915.

Tracking tests showed that receiver sensitivity to interference is greatest at 100 kHz and decreases as an interference signal gets farther from 100 kHz. Receivers are most sensitive to near-synchronous CWI, requiring 5 dB protection at 100 kHz. Curves were developed which present the minimum acceptable interference levels. Acquisition tests and uncertainties associated with background noise variation indicate that an additional 15 dB protection margin should be provided. Curves which include this additional margin were also produced.

LORAN-C receivers were also shown to be sensitive to interference beyond the authorized 90-110 kHZ emission band. A technique for analysis of the effects of emissions was developed and presented.

In view of the effect of interference, measures should be taken to prevent harmful interference through continuous monitoring of the Mobile Maritime Band and cooperation between operating agencies.

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